Quasiparticle recombination and competing orders in cuprate superconductors

Joe Orenstein
UC Berkeley and LBNL

Outline

(1) High-T_c: still crazy after 25 years

- Universal CDW phenomena in cuprates
- What we can learn from time-resolved reflectivity measurements

(2) Nonequilibrium quasiparticles: Hg 1201 system

- Elucidate cuprate phase diagram

(3) Nonequilibriuim quasiparticles: YBCO Ortho III, VIII

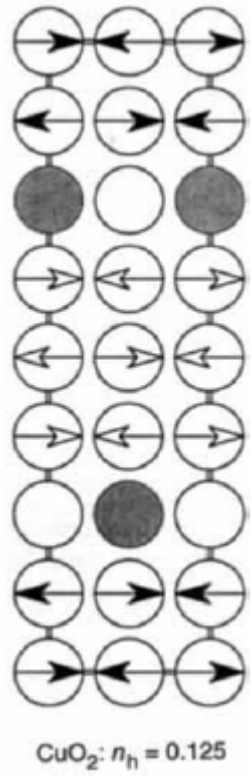
- CDW collective mode

(4) Evidence for mixed CDW + SC phase fluctuations

- "Cusp" in quasiparticle lifetime at T_c

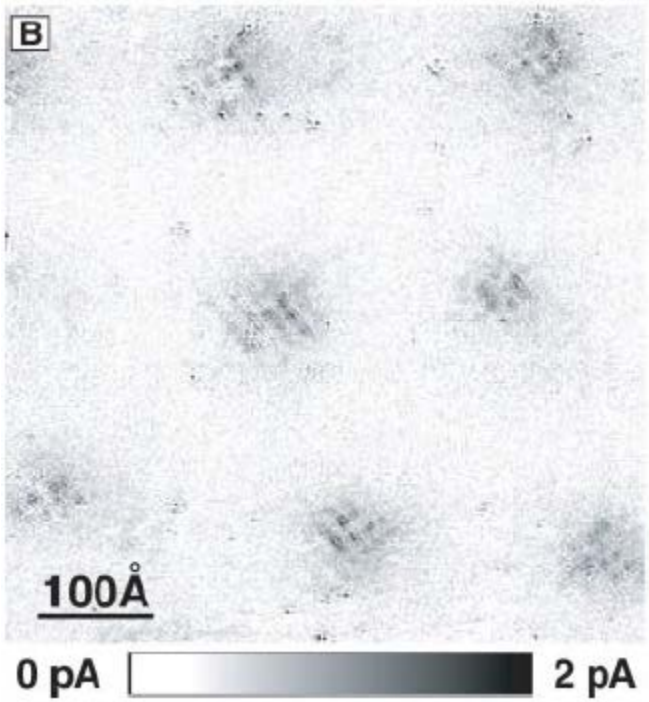
Charge order in cuprates

LSCO



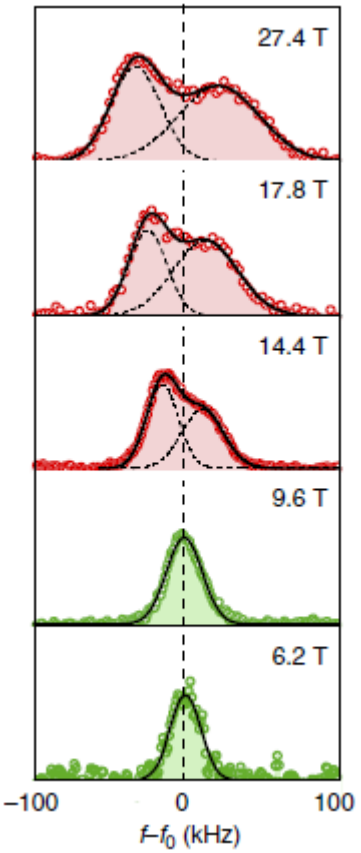
J. Tranquada et. al. Nature (1995)

BSCCO



J. Hoffman et al. Science (2002)

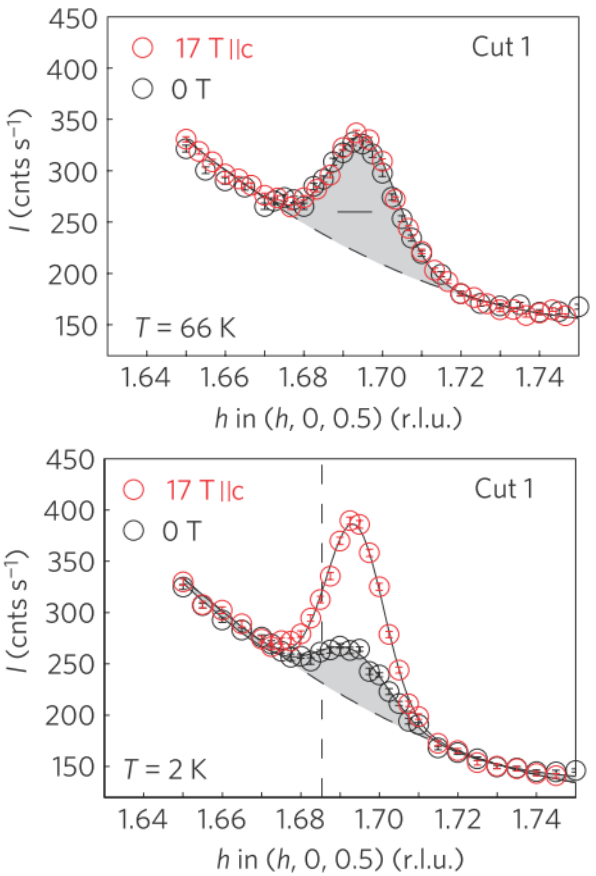
YBCO



- T. Wu et al. Nature. (2011)

Charge-Density Wave in YBCO

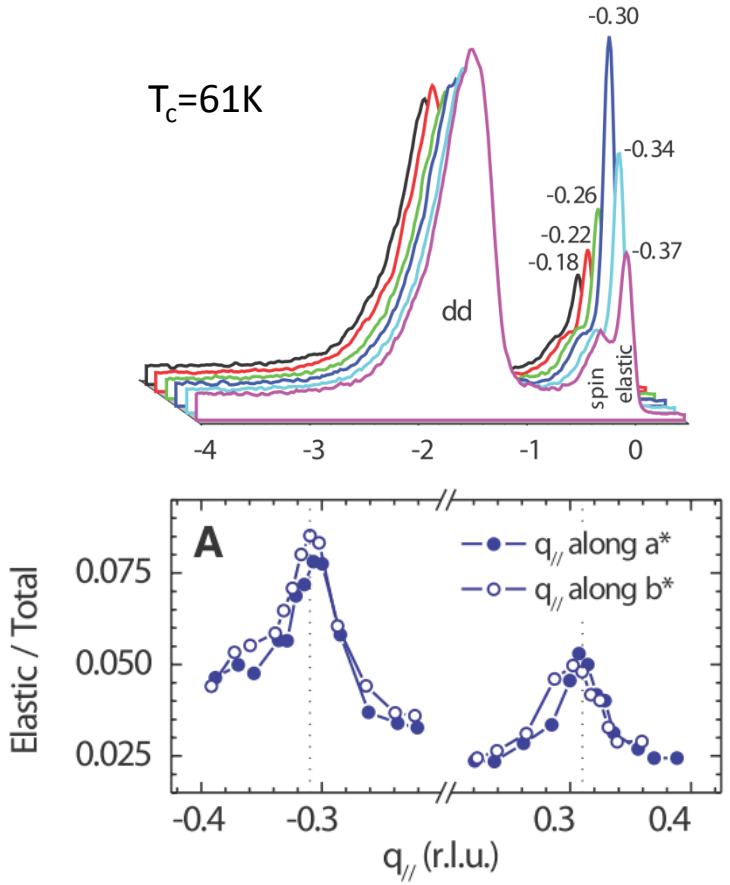
T_c=67K



q_a = (0.3045,0), q_b = (0,0.3146) ; ξ_a = 24 ± 1

Chang *et al.*, Nature Phys. (2012)

T_c=61K

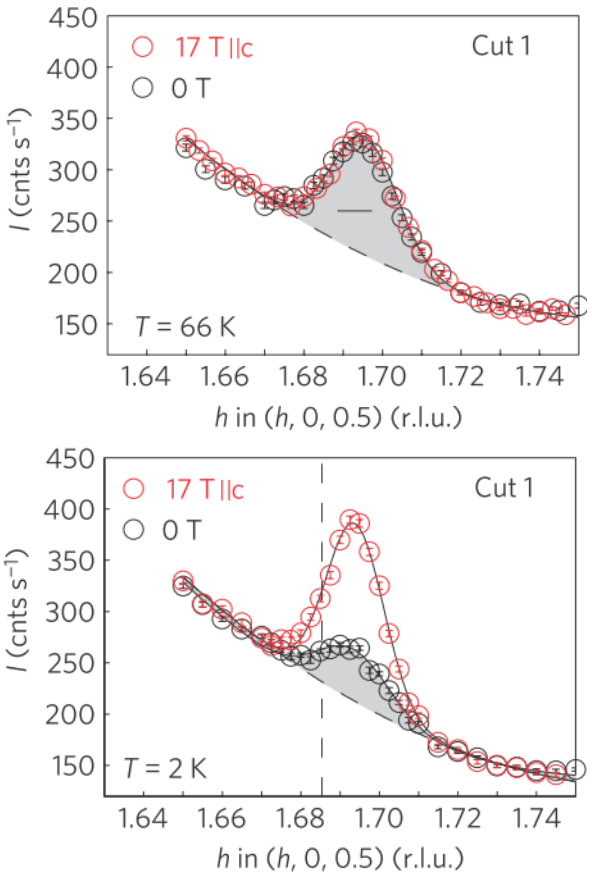


$q_{//}$ = (0.31,0), ξ_a = 16 ± 2

Ghiringhelli *et al.*, Science (2012)

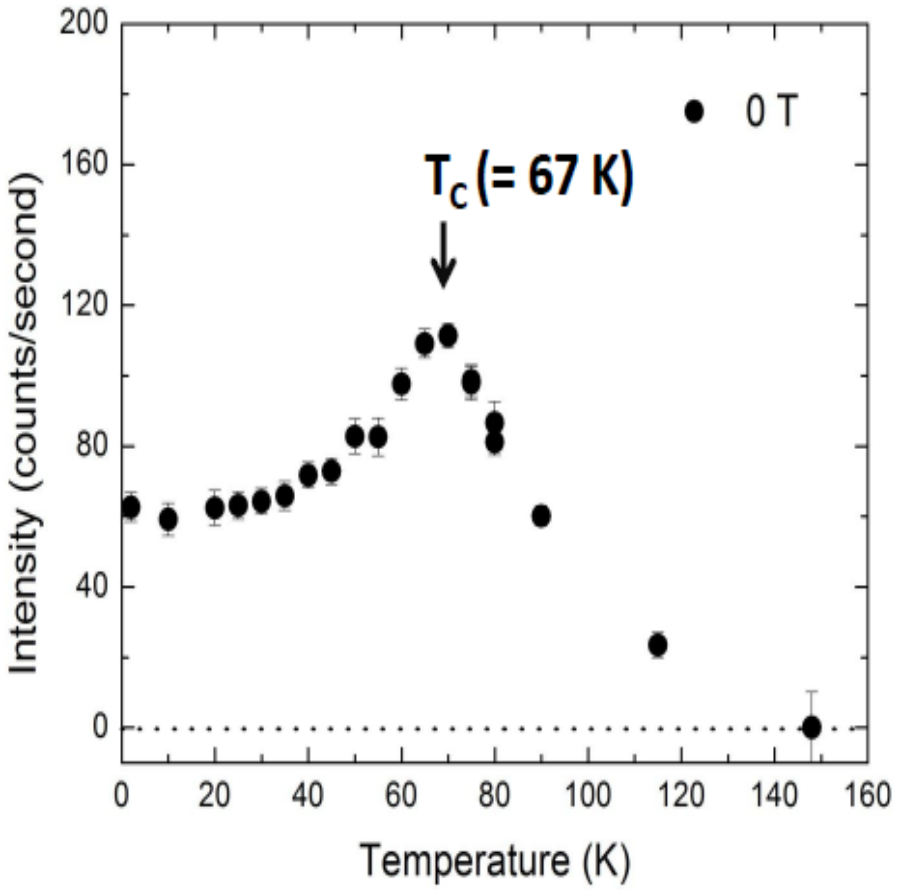
Charge-Density Wave in YBCO

T_c=67K



q_a = (0.3045,0), q_b = (0,0.3146) ; ξ_a = 2

Chang *et al.*, Nature Phys. (2012)

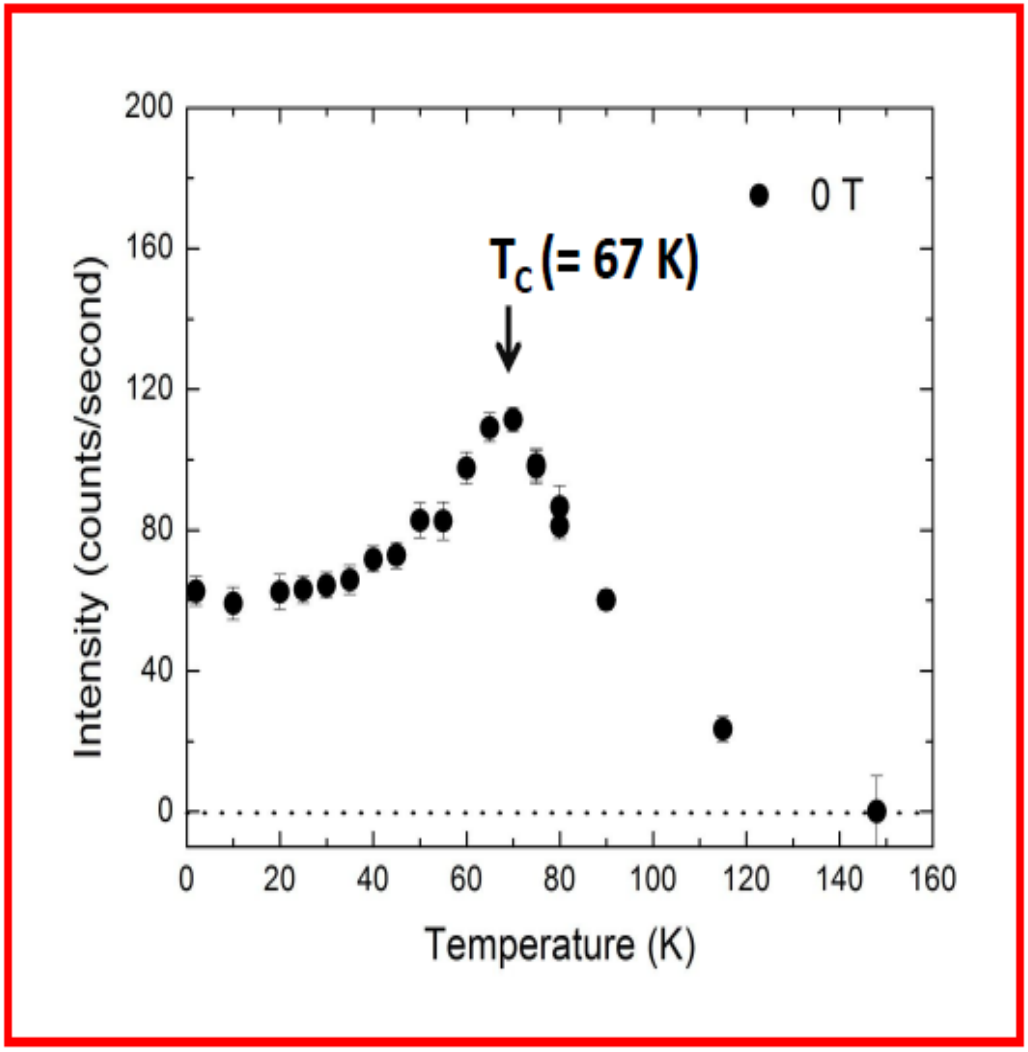


Charge-Density Wave in YBCO

Possible origin of pseudogap

CDW nearly degenerate with SC

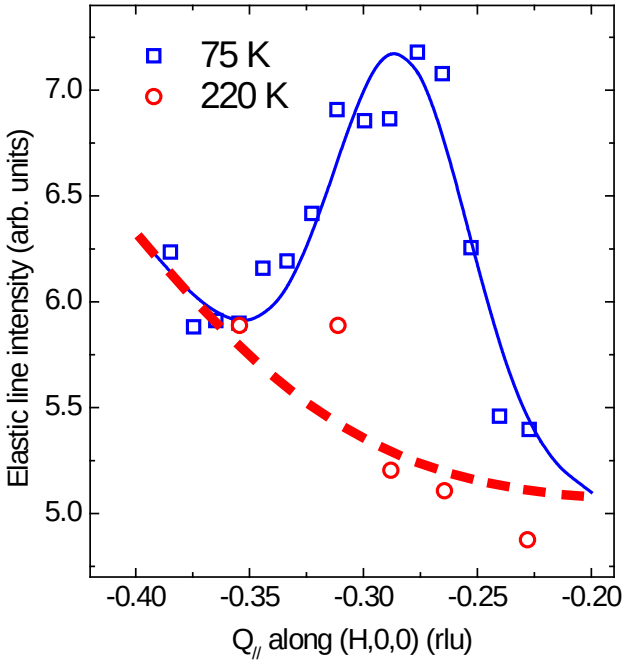
Direct evidence of “competition”

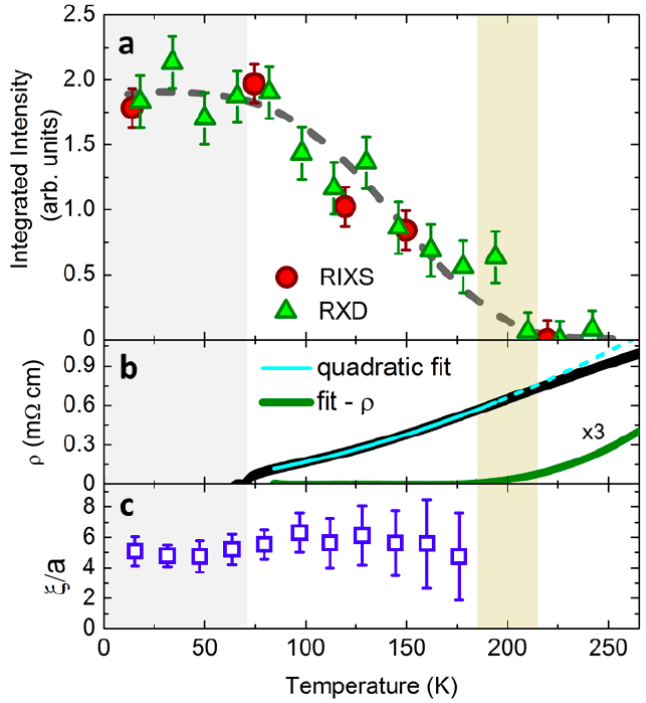


Evidence for universality: CDW in Hg1201 (T_c = 71 K)

W. Tabis *et al.* (unpublished)

Cu L-edge Resonant Soft X-Ray Scattering

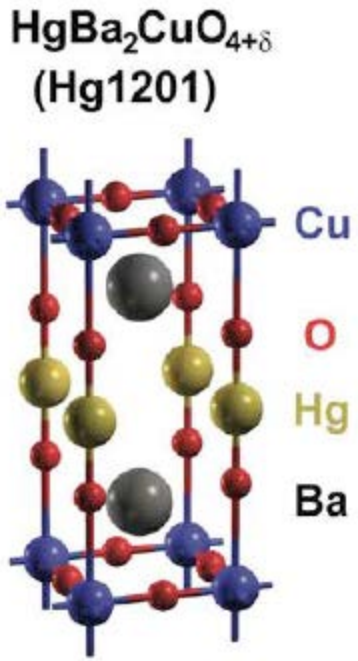


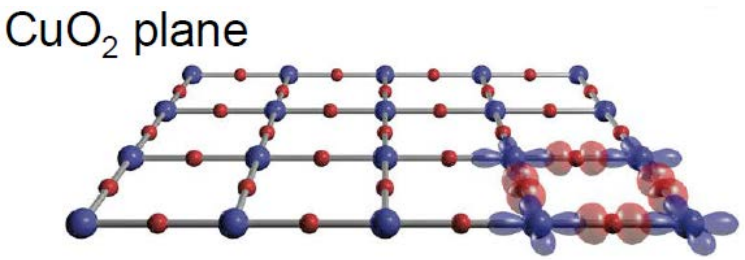


- $q_{//} \approx (0.28,0)$ and $\xi/a \approx 5 \pm 1$; no temperature dependence
- No significant intensity decrease below T_c
- $T_{CDW} \approx T^{**}$

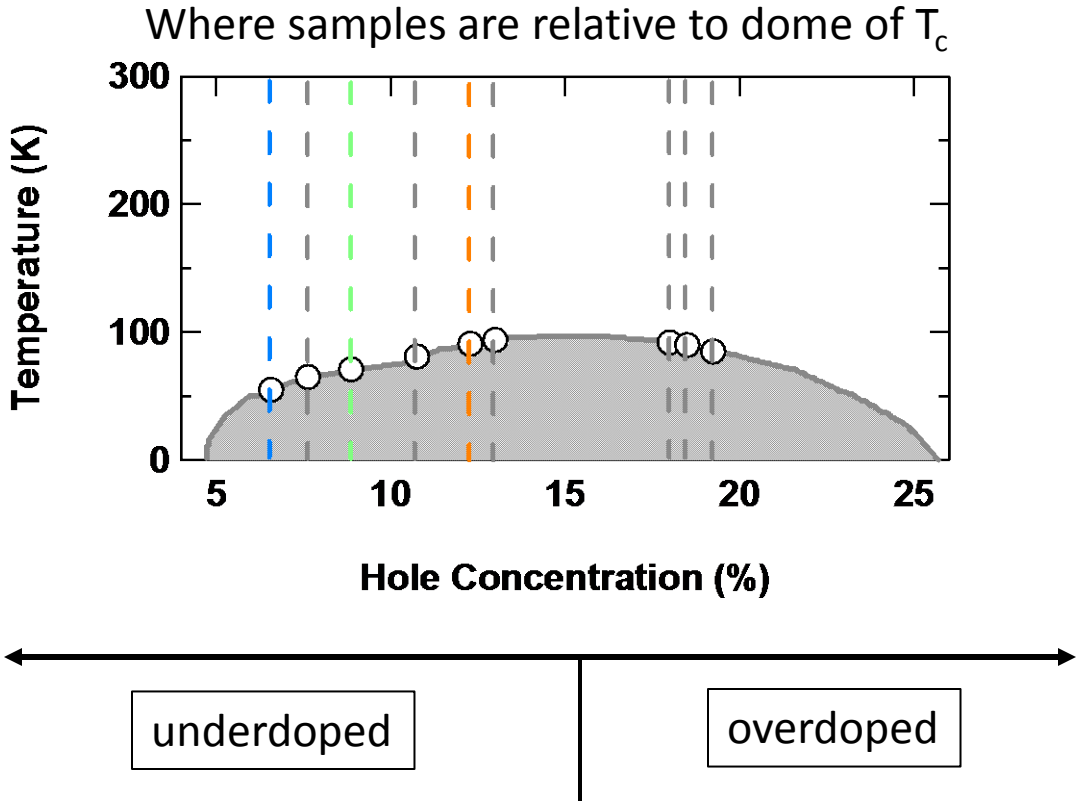
Model cuprate superconductor $HgBa_2CuO_{4+\delta}$

Martin Greven
(University of Minnesota)

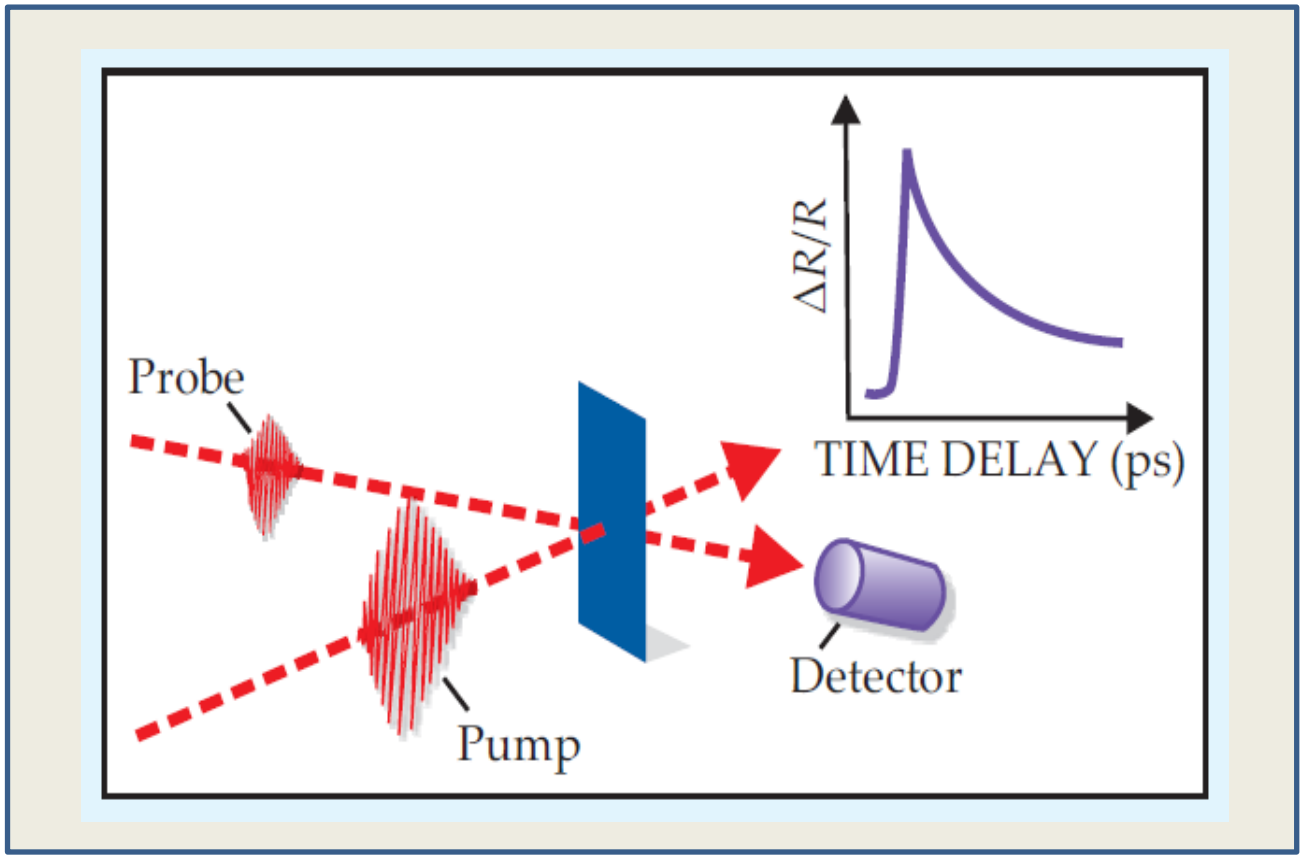




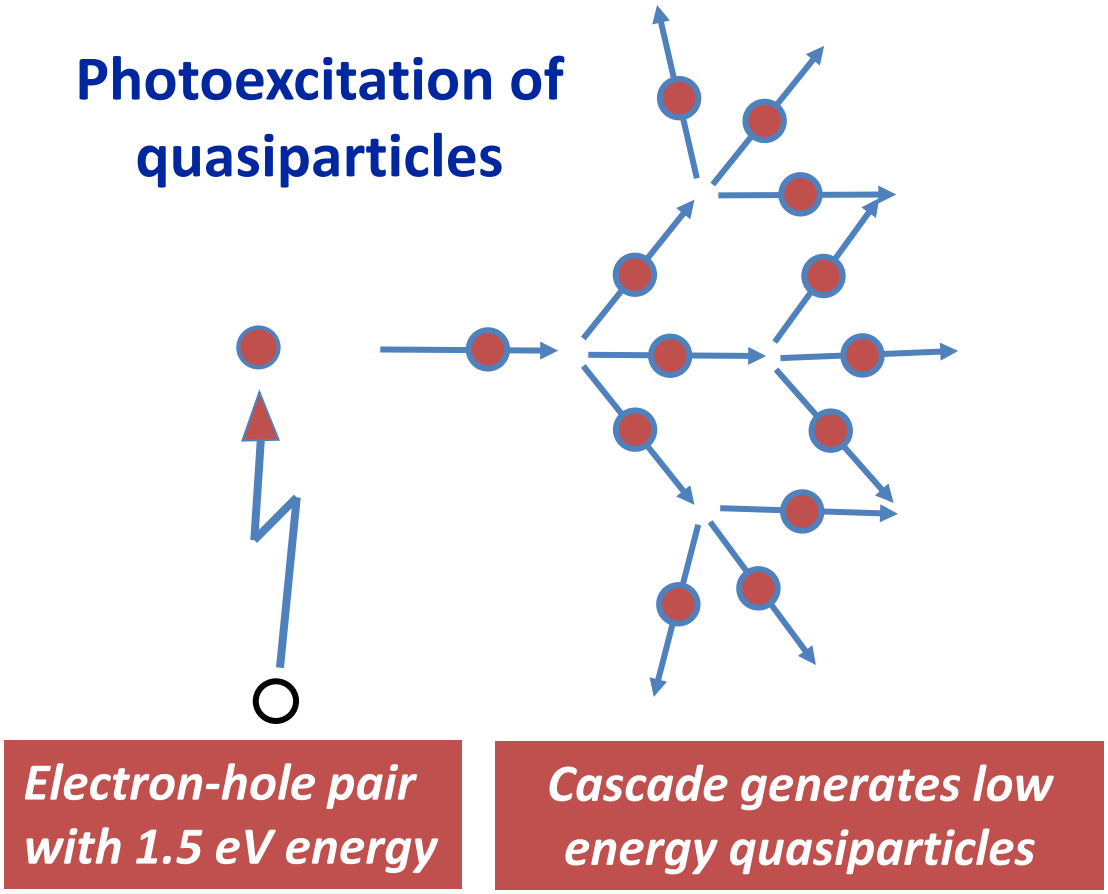
Track $\Delta R(t)$ across SC dome



What can we learn from time-resolved reflectivity?

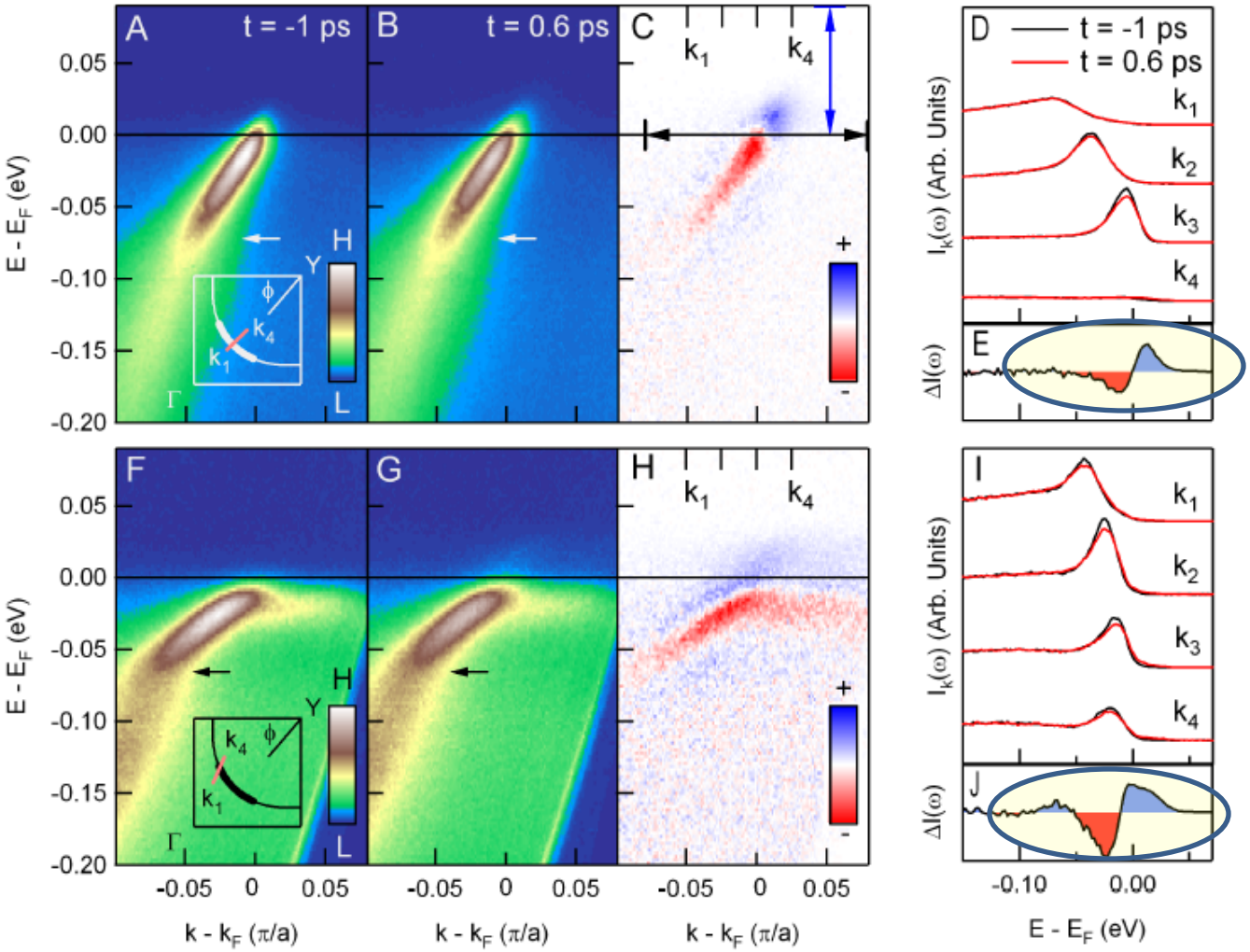


Non-equilibrium quasiparticles generated by photons



Quasiparties thermalize to E_F (t < 1 ps)

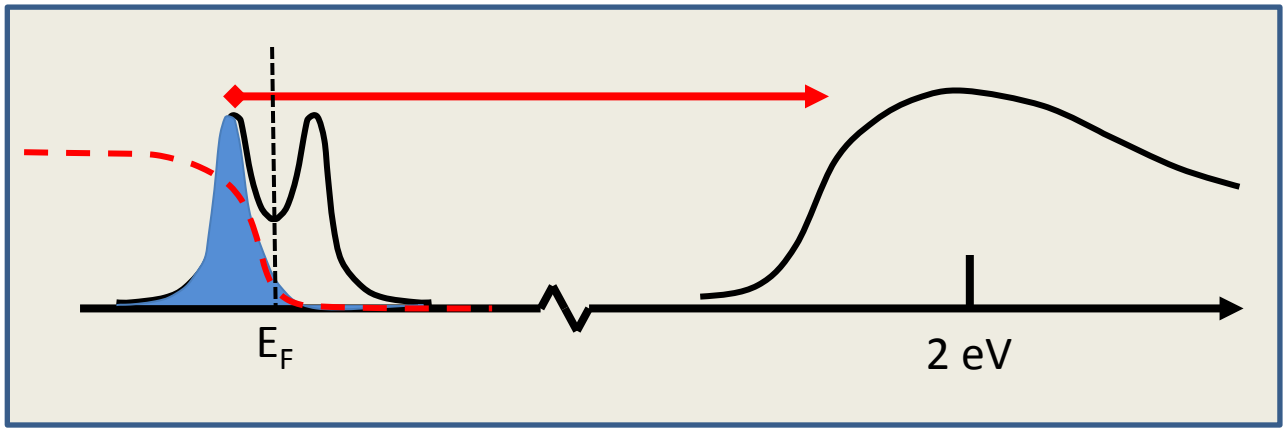
Time-resolved ARPES C. L. Smallwood et al. Science 336, 1137 (2012)



Time-resolved reflectivity: “internal photoemission”

Equilibrium

$f(\varepsilon)A(\varepsilon)$

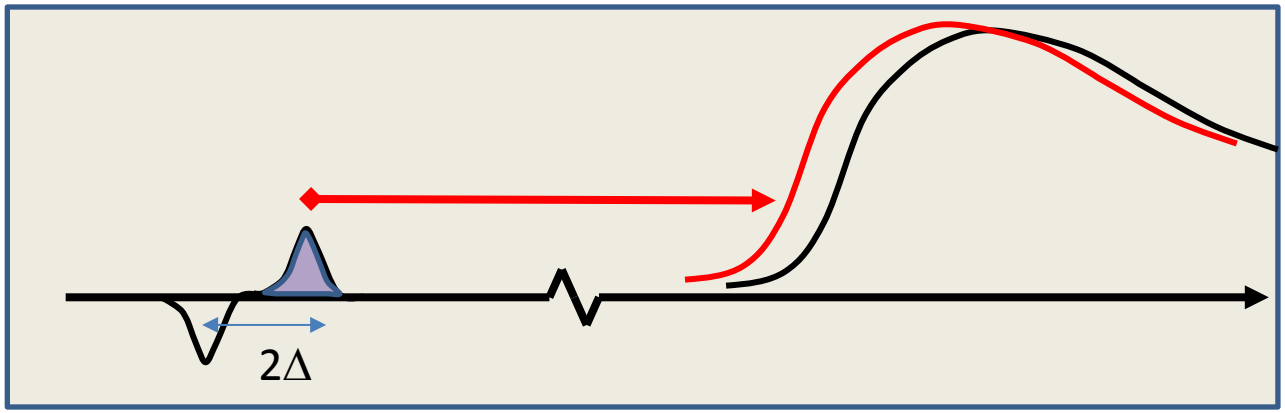


Now excite quasiparticles…

Interband transition “red-shifted” by first moment of spectral weight shift

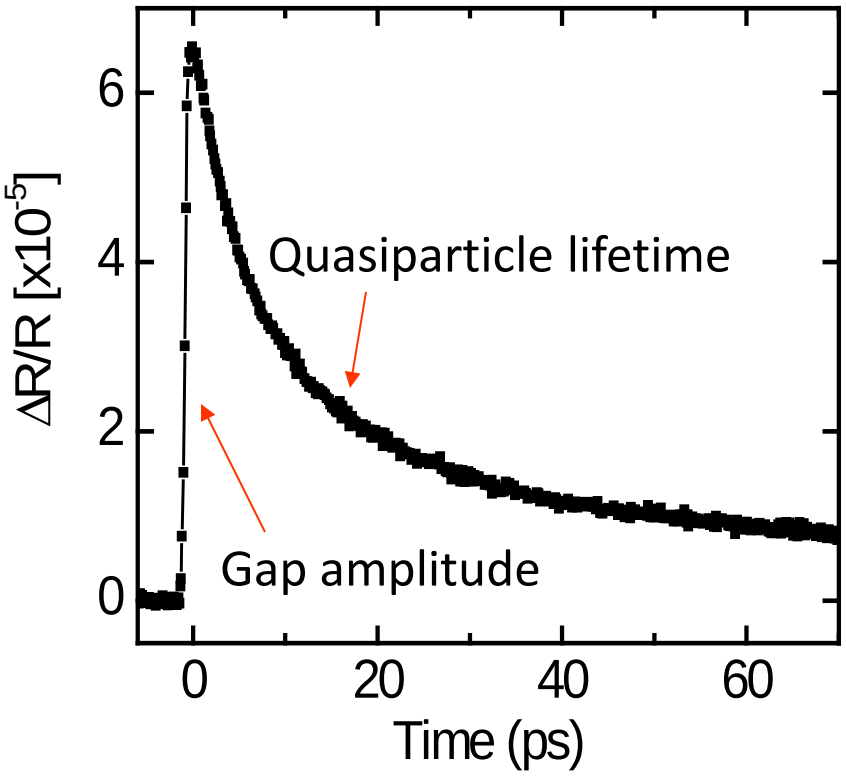
Change in equilibrium

$\delta[f(\varepsilon)A(\varepsilon)]$



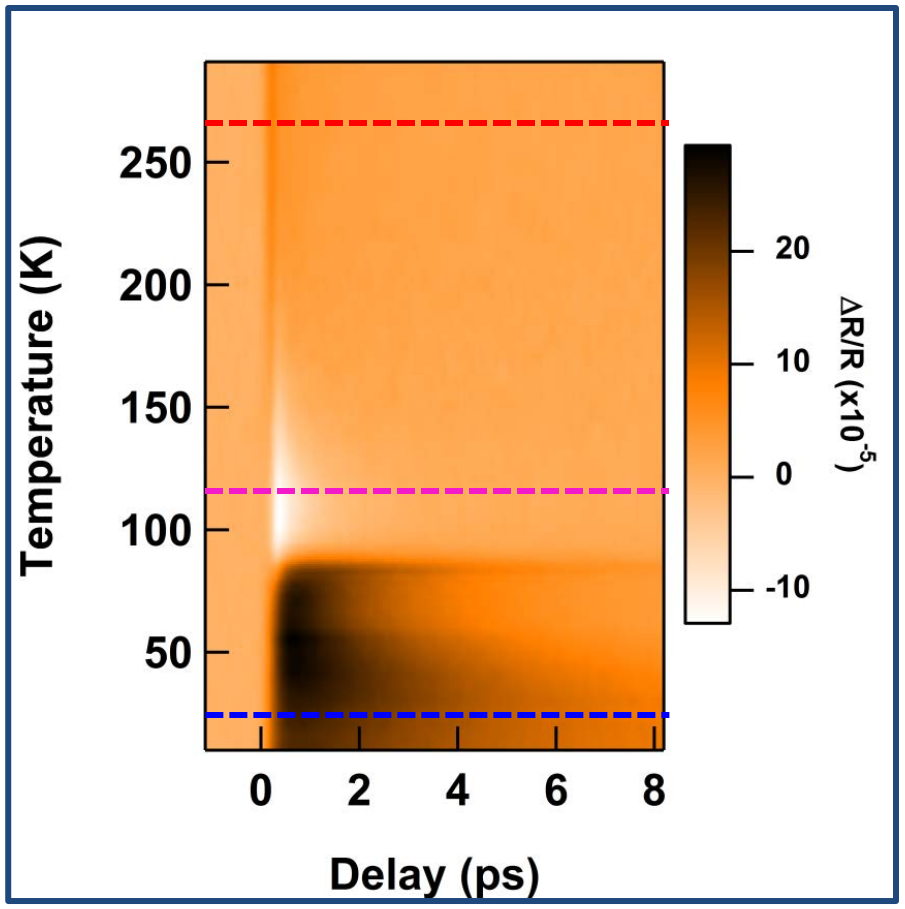
Summary of information in $\Delta R(t)$

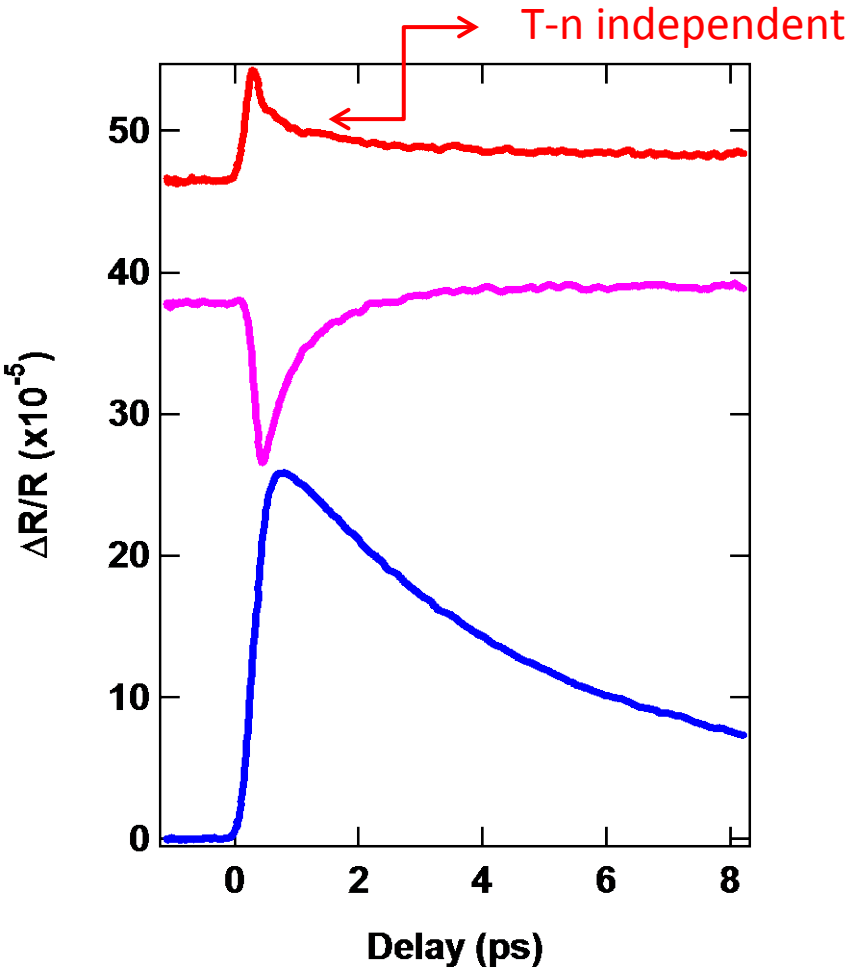
$\Delta R(0)$ measures **gap size** though first moment of spectral weight shift
Decay [$\Delta R(t)$] measures quasiparticle recombination rate



Three components of ΔR in underdoped Hg1201

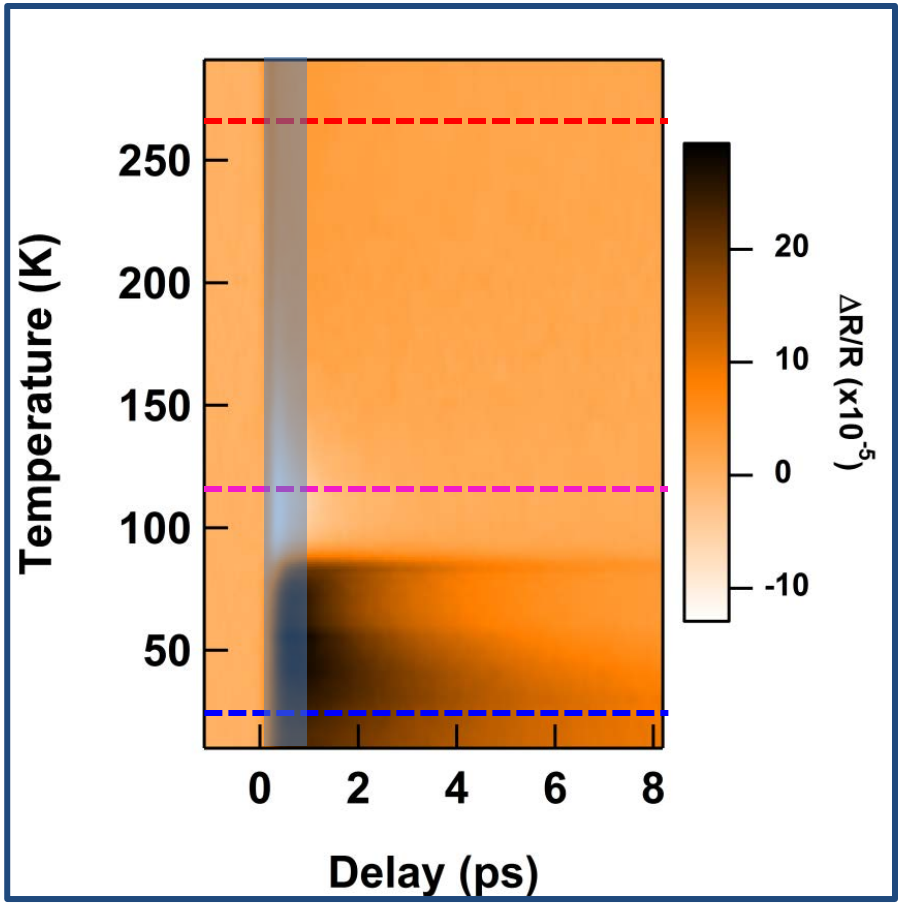
T_c = 90 K

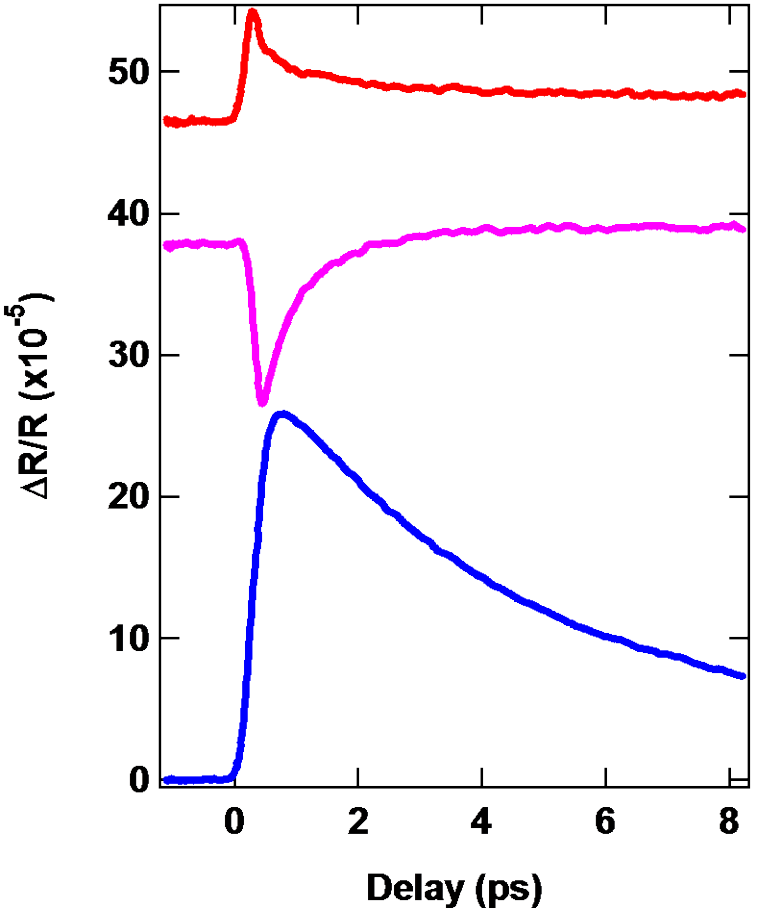




Focus on initial amplitude of ΔR

T_c = 90 K





Focus on initial amplitude of ΔR

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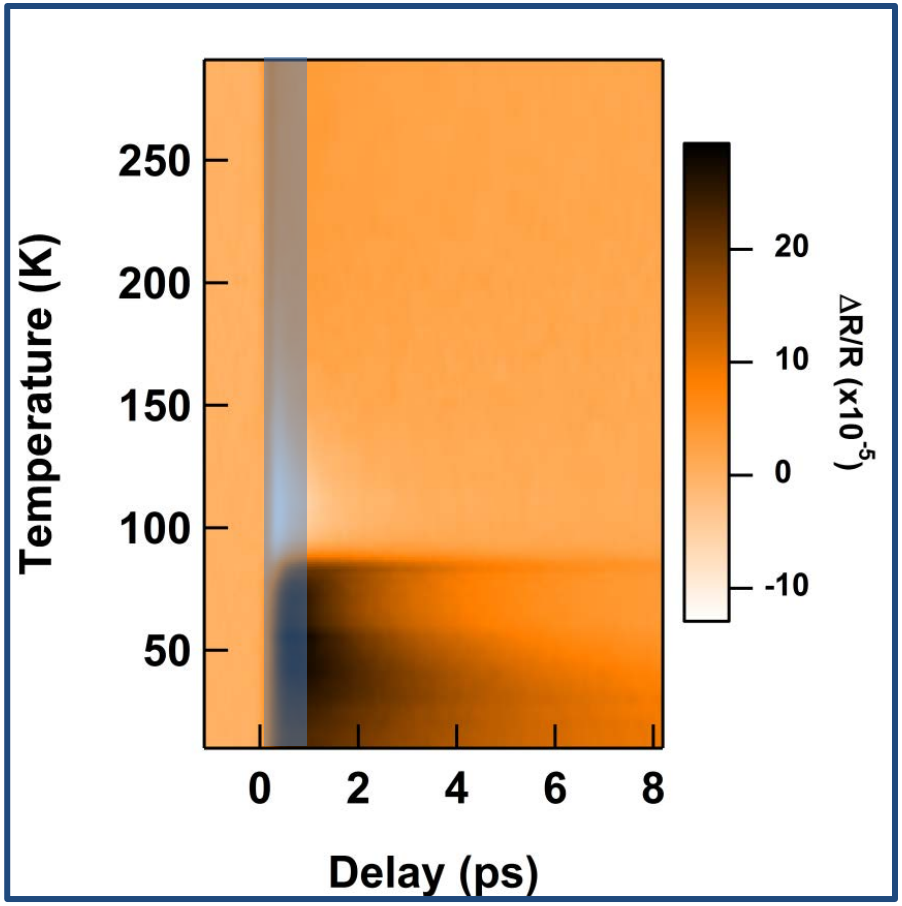
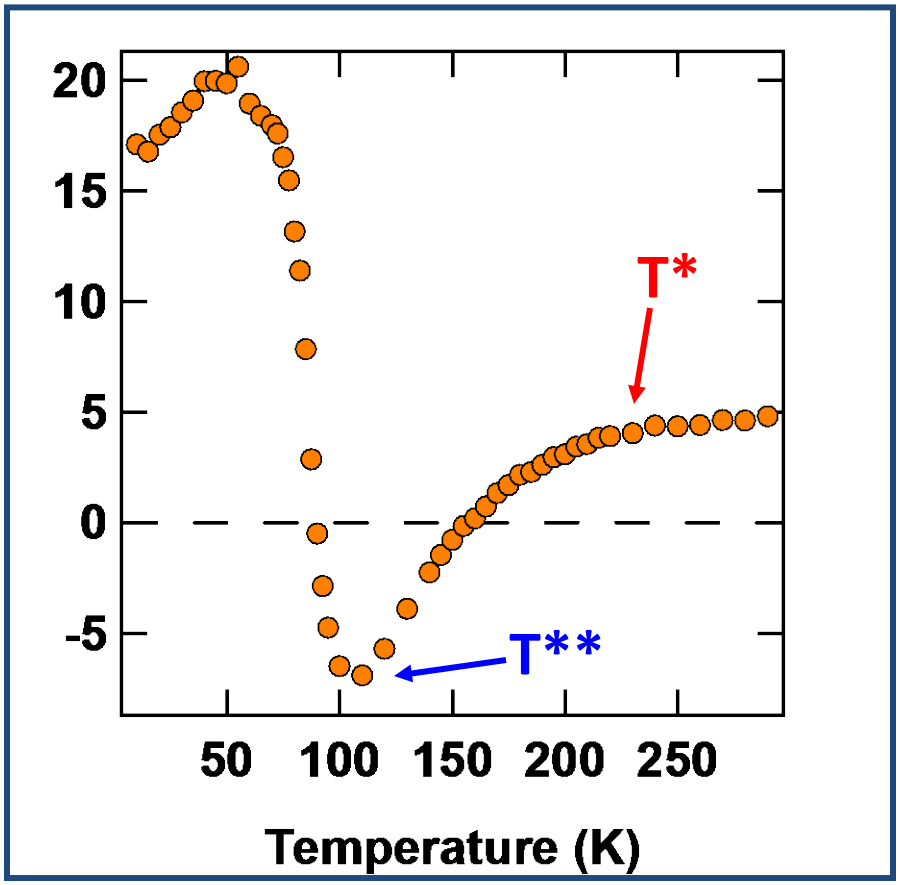
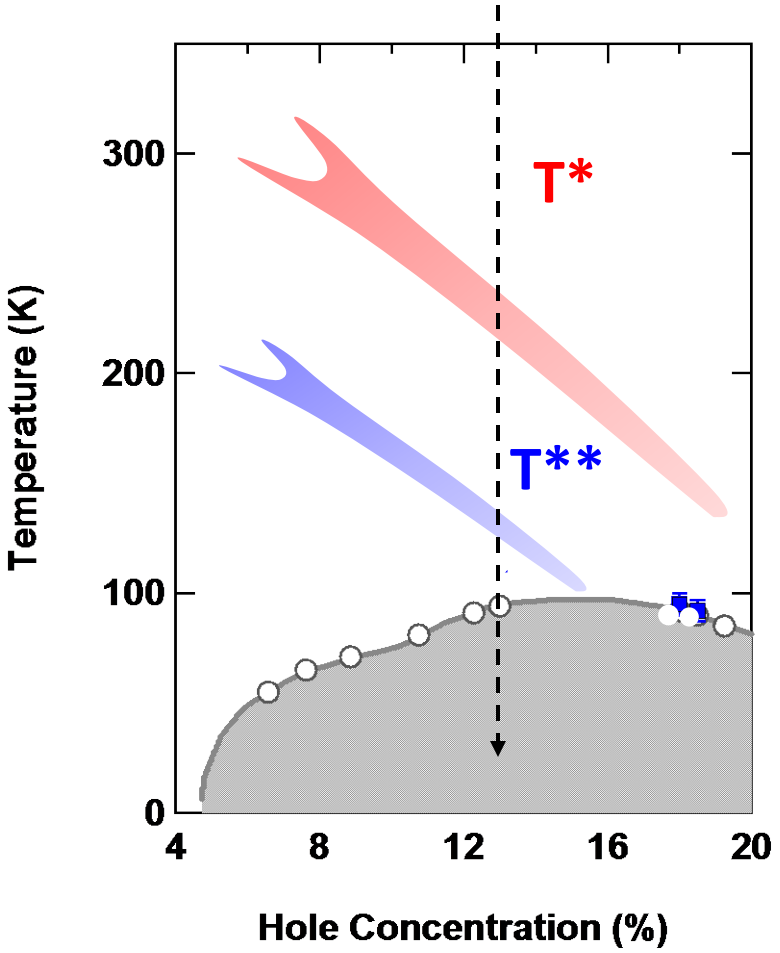
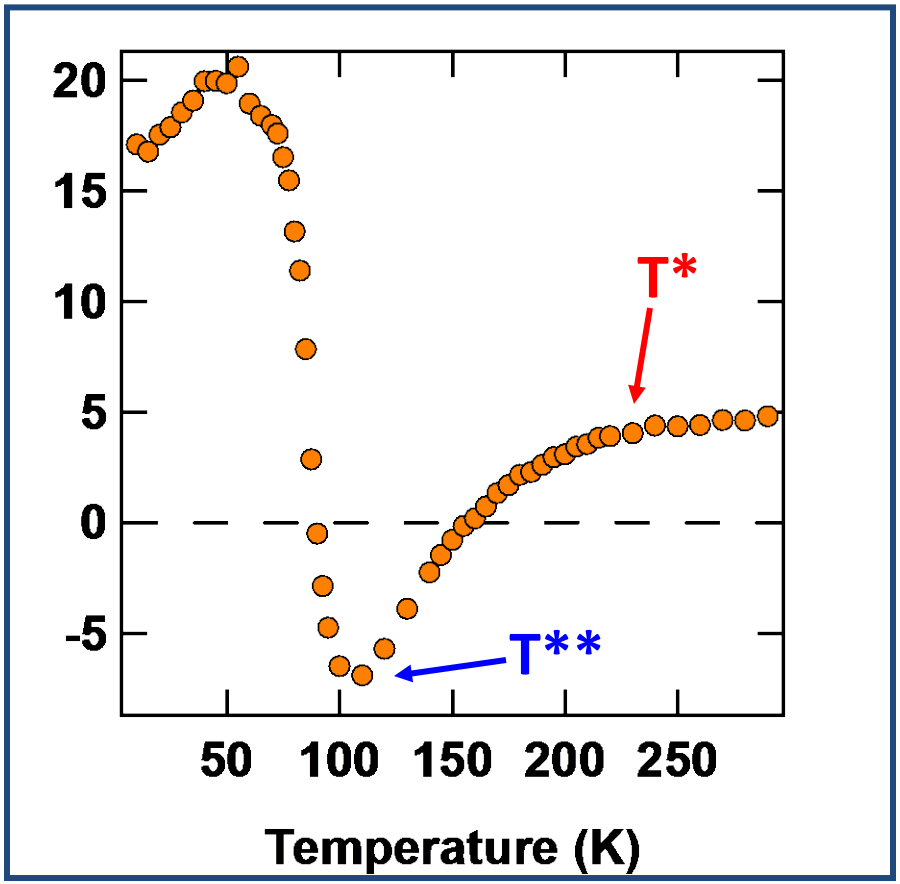


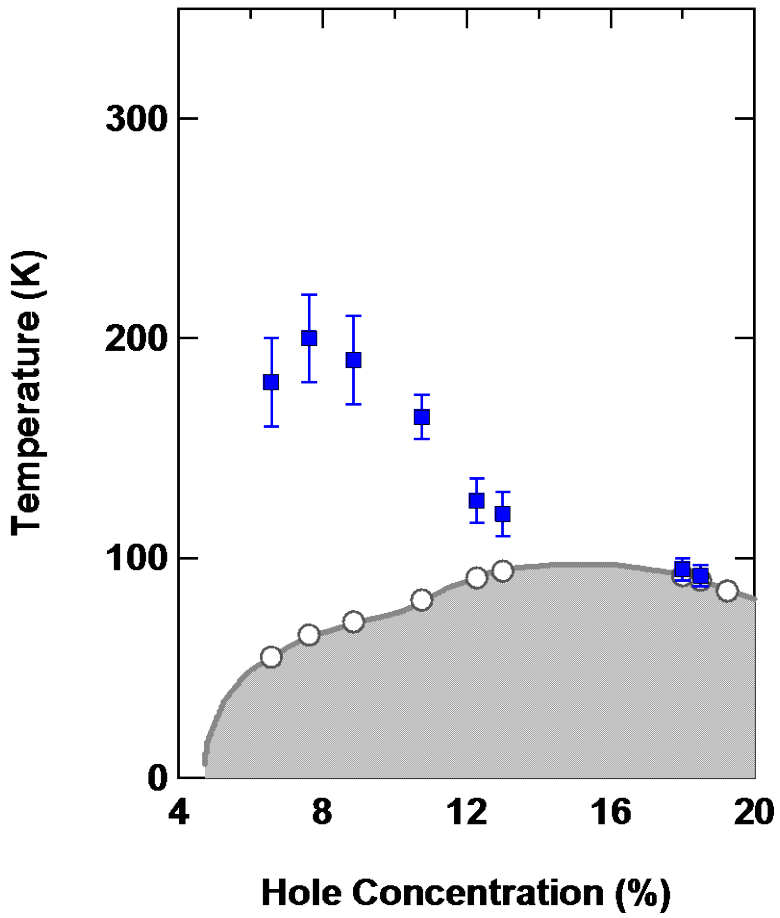


Focus on initial amplitude of ΔR



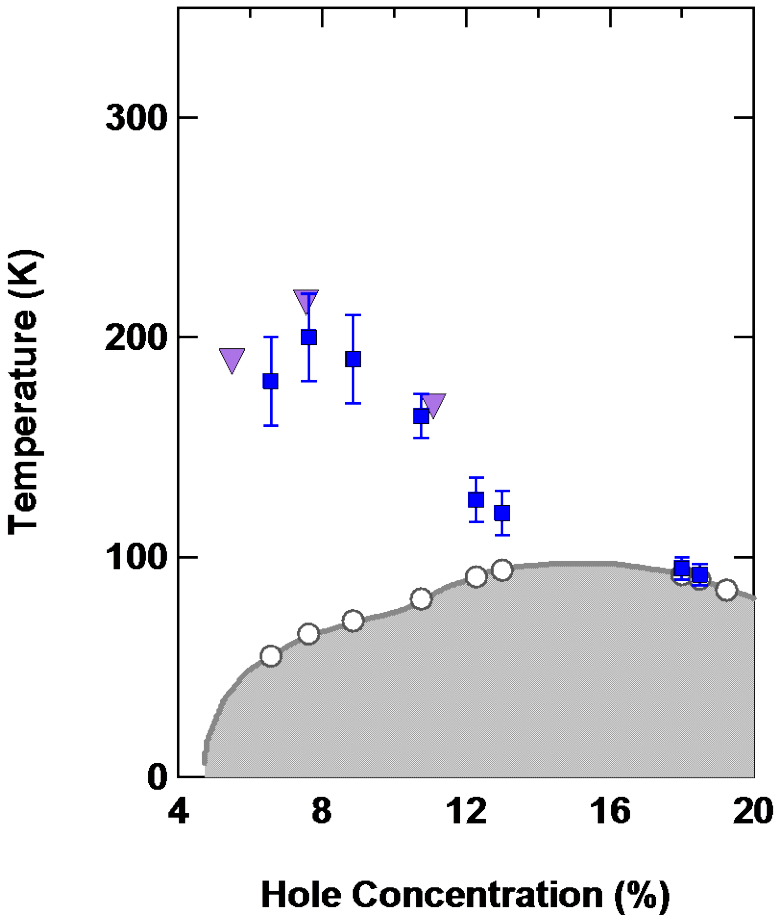


Correlation with T** and CDW onset T



T* (onset of positive ΔR)

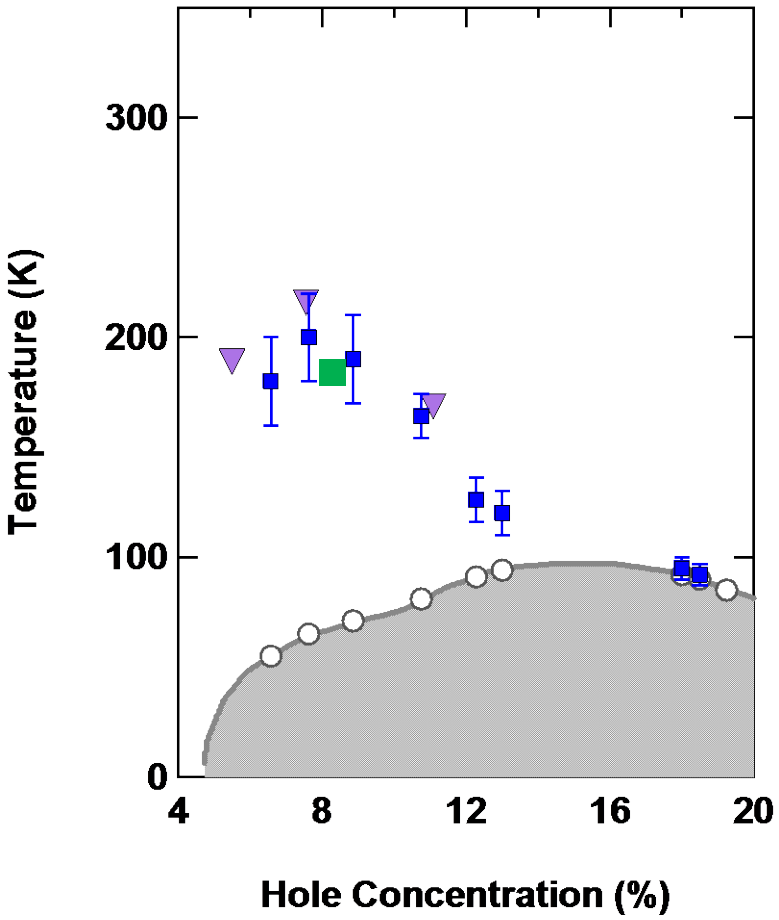
Correlation with T** and CDW onset T



T** (onset of positive ΔR)

T** (transport, Greven group)

Correlation with T** and CDW onset T



T** (onset of positive ΔR)

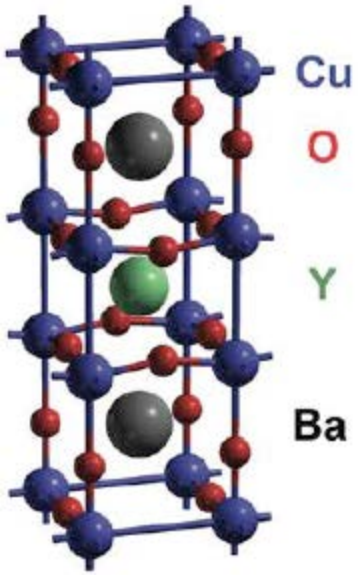
T** (transport, Greven group)

CDW

Related observation in YBCO

UBC	**Ruixing Liang**, Doug Bonn, Walter Hardy
MPI Stuttgart	**Bernhard Keimer** Mathieu Le Tacon, Toshinao Loew

$YBa_2Cu_3O_{7-\delta}$
(YBCO)

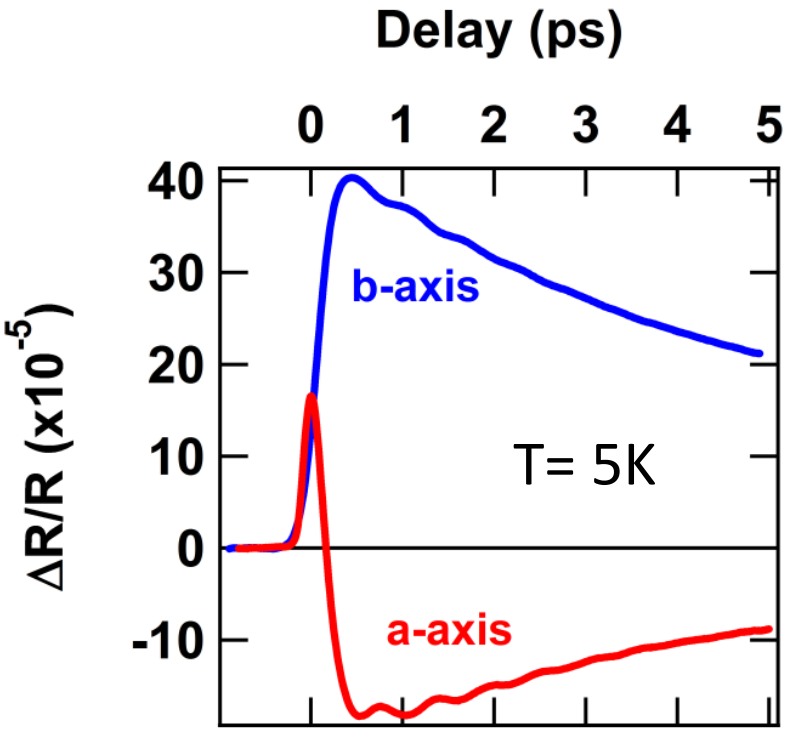


- Ortho II [T_c = 61 K]
- Ortho VIII [T_c = 67 K]
- Ortho III [T_c = 77 K]

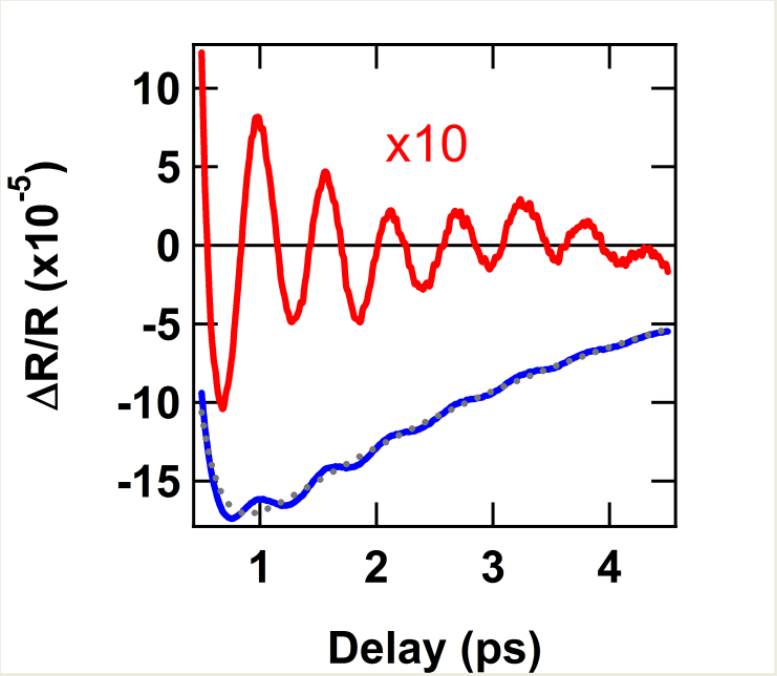
Observation of CDW collective mode in YBCO

J. Hinton et al. PHYSICAL REVIEW B 88, 060508(R) (2013)

Transient reflectivity in YBCO ortho VIII (T_c = 66K)



Expanded view showing oscillations

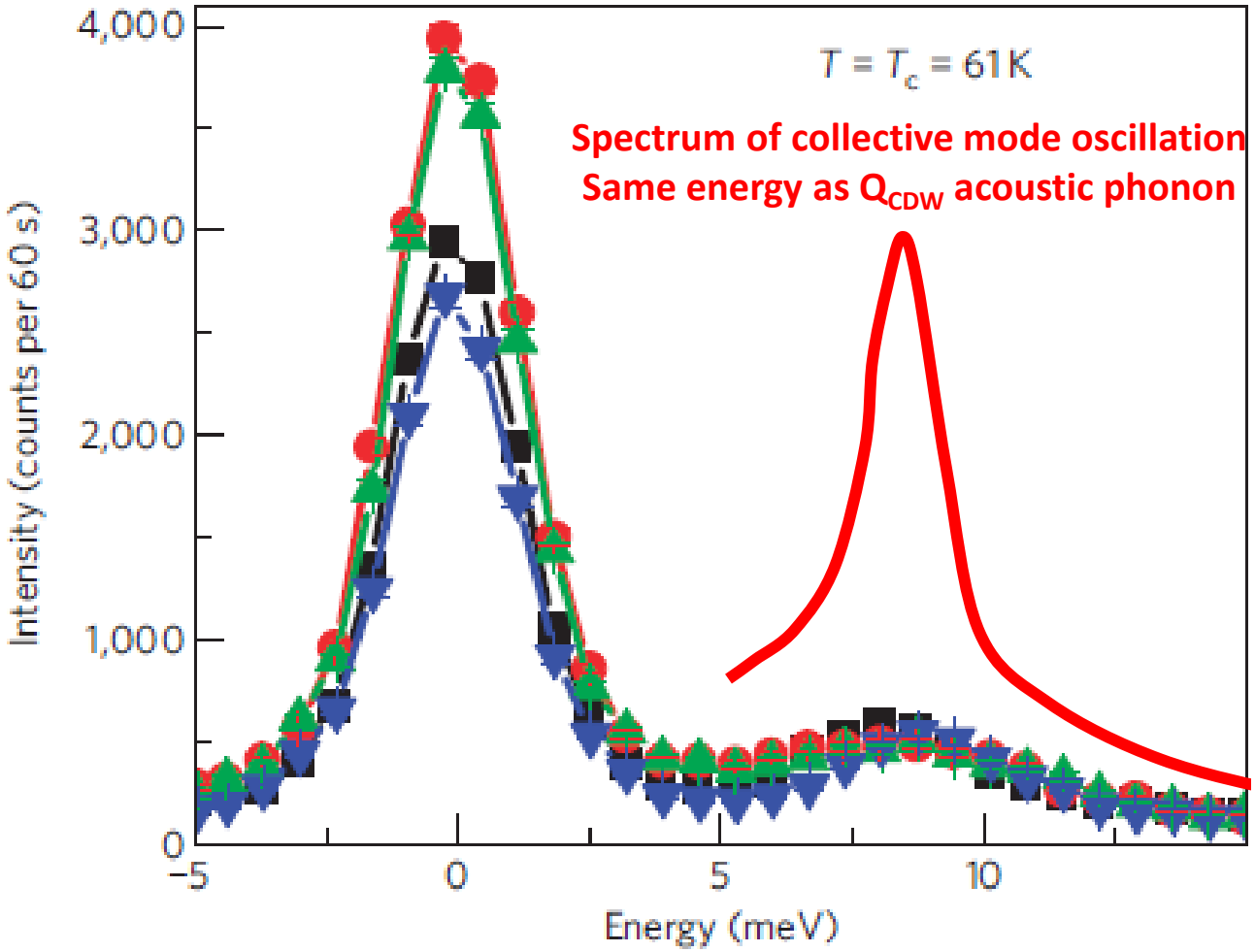


Connection with CDW: inelastic X-ray scattering spectrum measured at Q_{CDW}

ARTICLES
PUBLISHED ONLINE: 24 NOVEMBER 2013 | DOI: 10.1038/NPHYS2805
nature physics

Inelastic X-ray scattering in $YBa_2Cu_3O_{6.6}$ reveals giant phonon anomalies and elastic central peak due to charge-density-wave formation

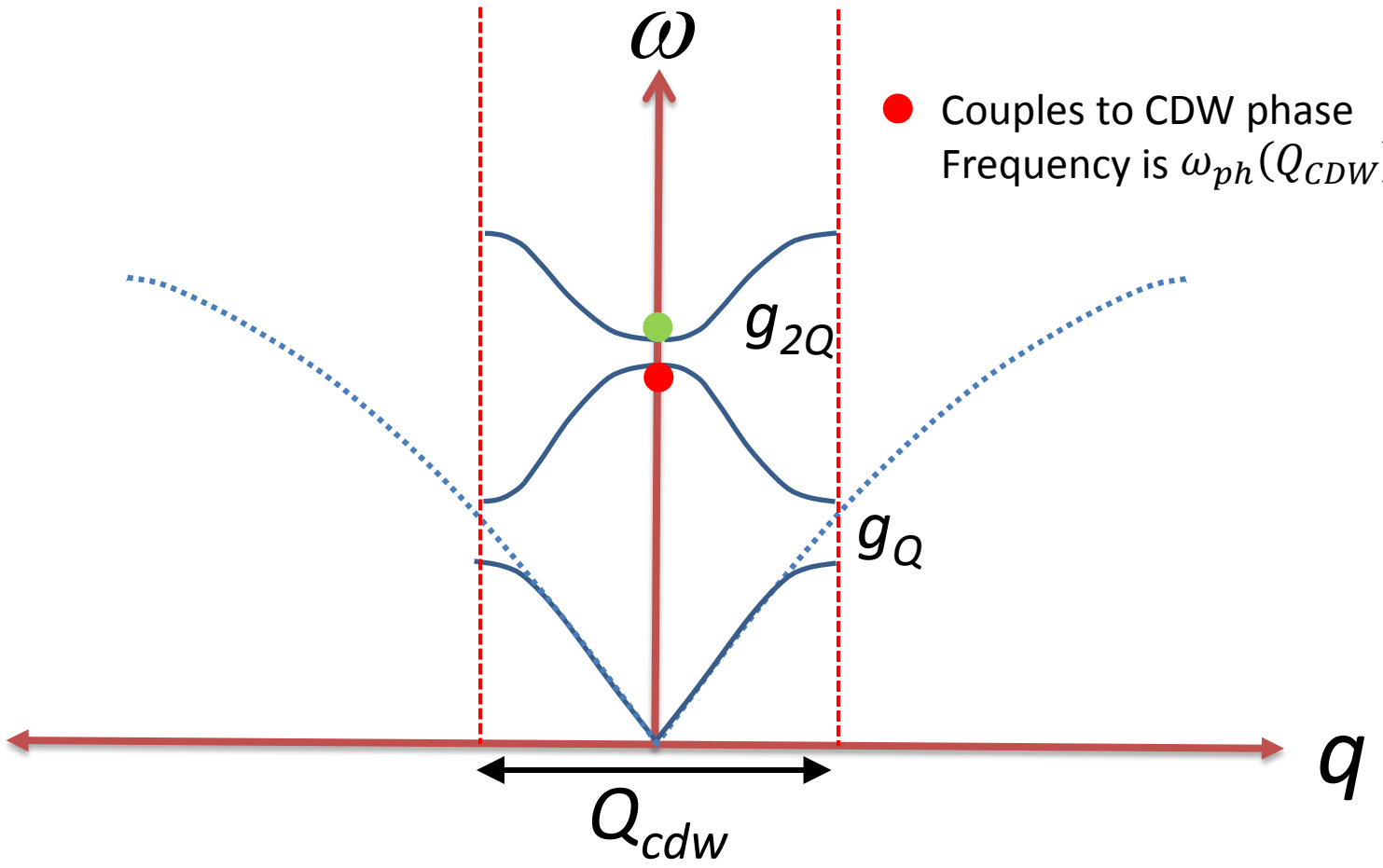
M. Le Tacon[1]*, A. Bosak[2], S. M. Souliou[1], G. Dellea[3], T. Loew[1], R. Heid[4], K-P. Bohnen[4], G. Ghiringhelli[3], M. Krisch[2] and B. Keimer[1]*



Phonon dispersion and CDW collective mode

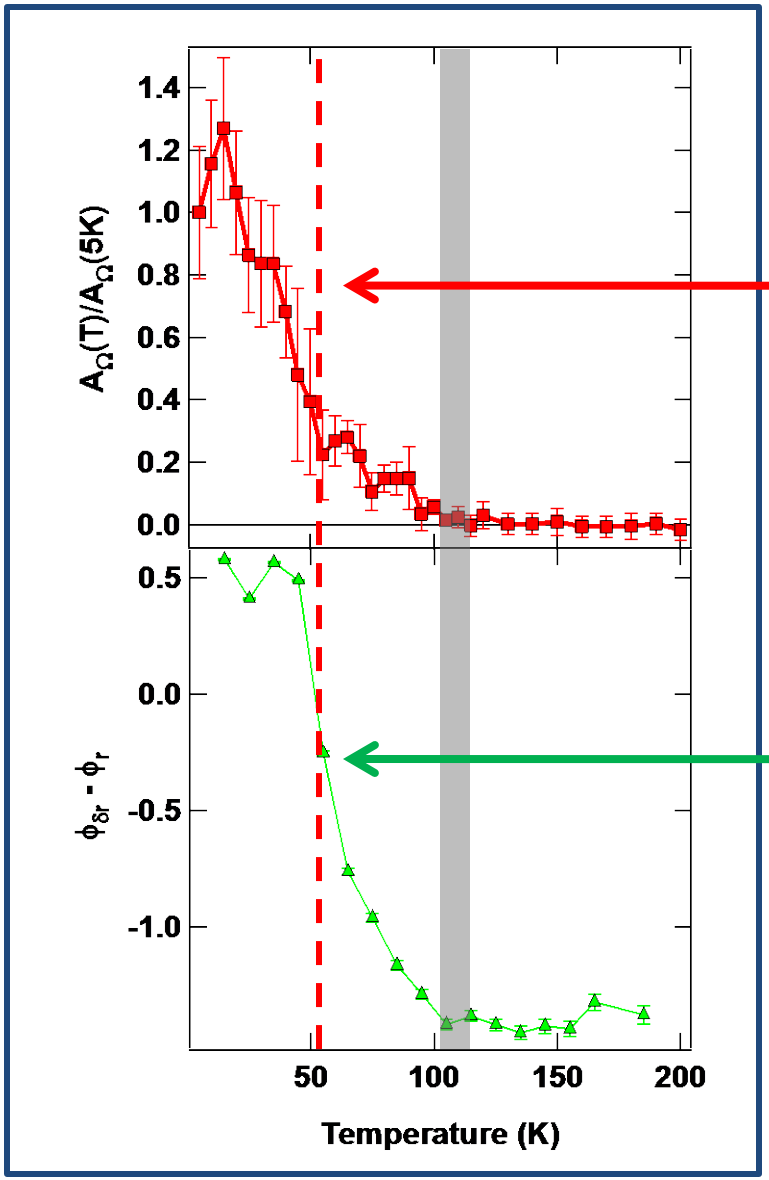
Couples to CDW amplitude
Frequency is $\omega_{ph}(Q_{CDW}) + g_{2Q}$

Couples to CDW phase
Frequency is $\omega_{ph}(Q_{CDW}) - g_{2Q}$



Collective mode probes second spatial harmonic of CDW amplitude
The fact that the new optic mode is close to $\omega_{ph}(Q_{CDW})$ indicates weak coupling

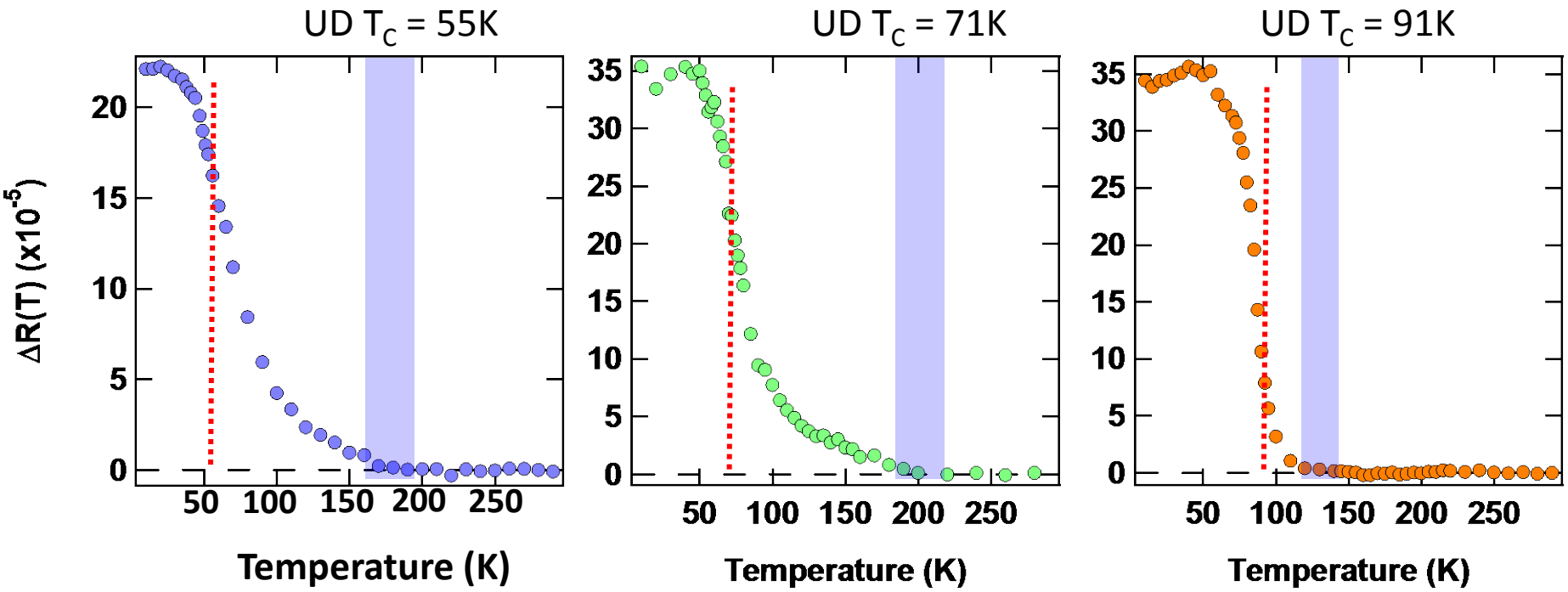
Onset of collective mode amplitude correlated with component of $\Delta R/R$



Collective mode amplitude

$\Delta R(t=0)$

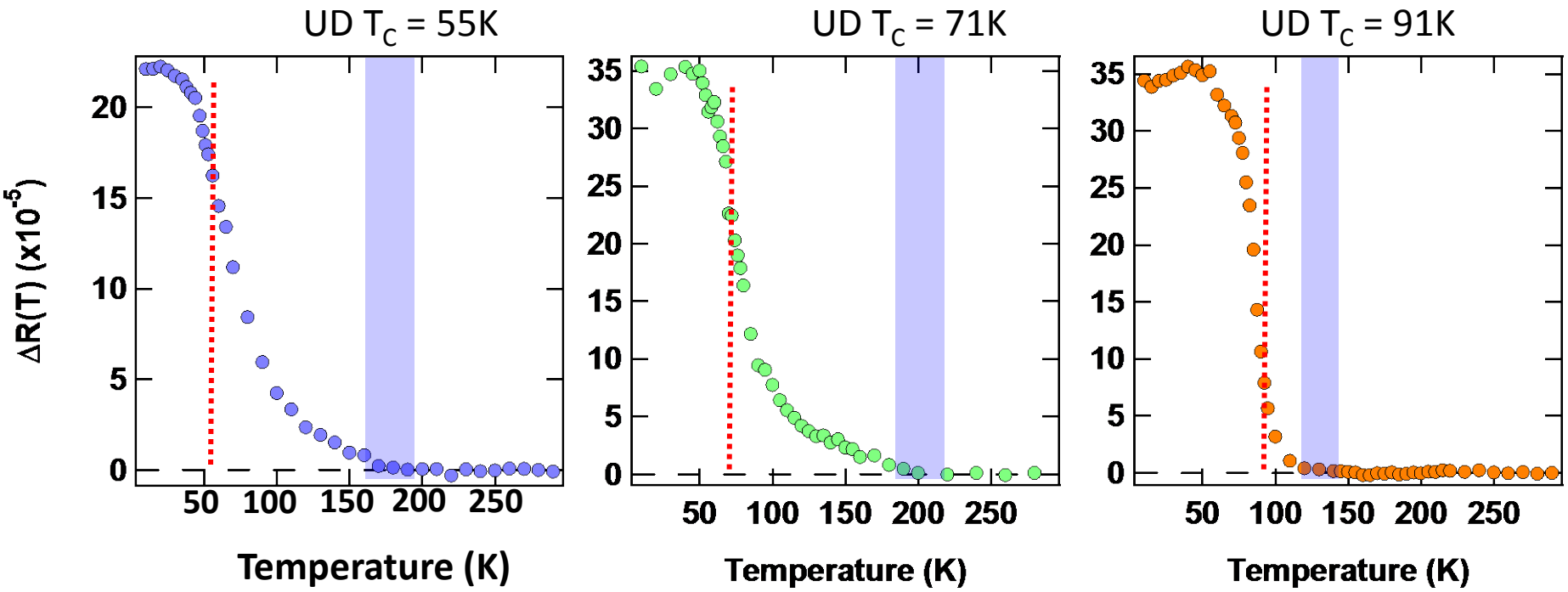
Gap amplitude $\Delta(T)$ in underdoped Hg1201



Gap appears at T_{CDW}

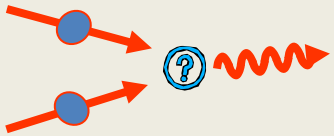
Amplitude is smooth through T_c

Gap amplitude $\Delta(T)$ in underdoped samples $T > T_c$



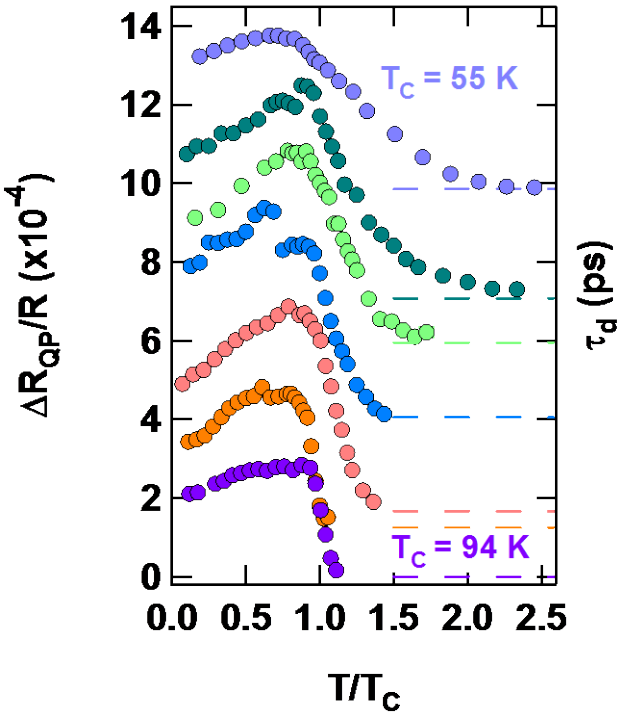
What about quasiparticle lifetime?

Quasiparticle recombination

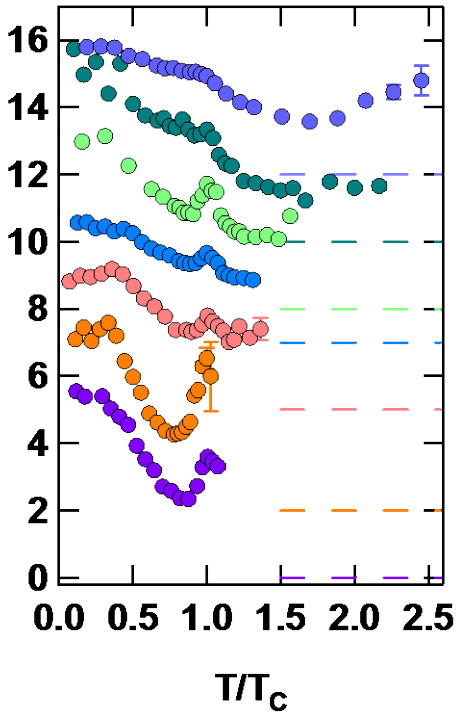


Cusp in quasiparticle lifetime at T_c

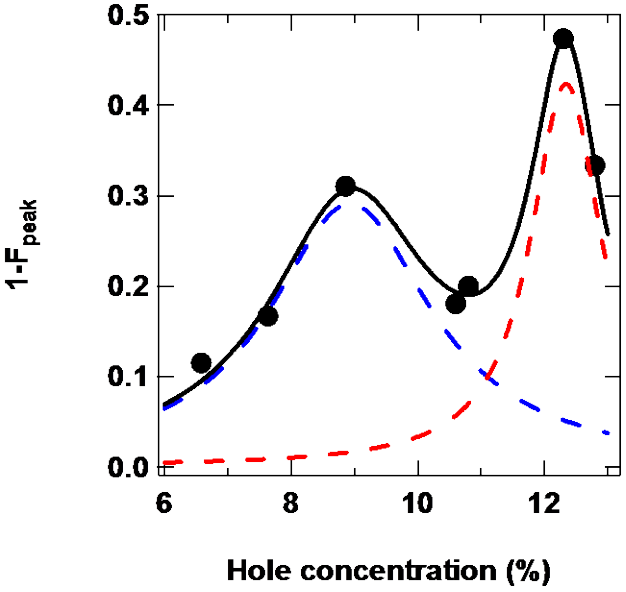
Gap amplitude



Quasiparticle lifetime



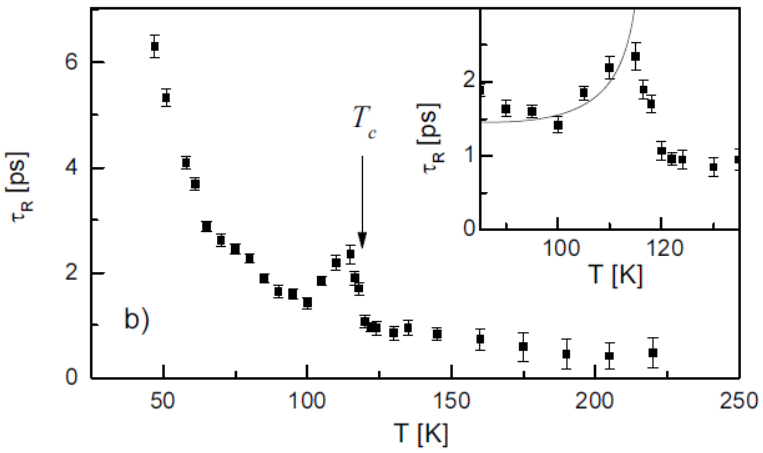
Cusp vs doping



Cusp in lifetime is a universal feature

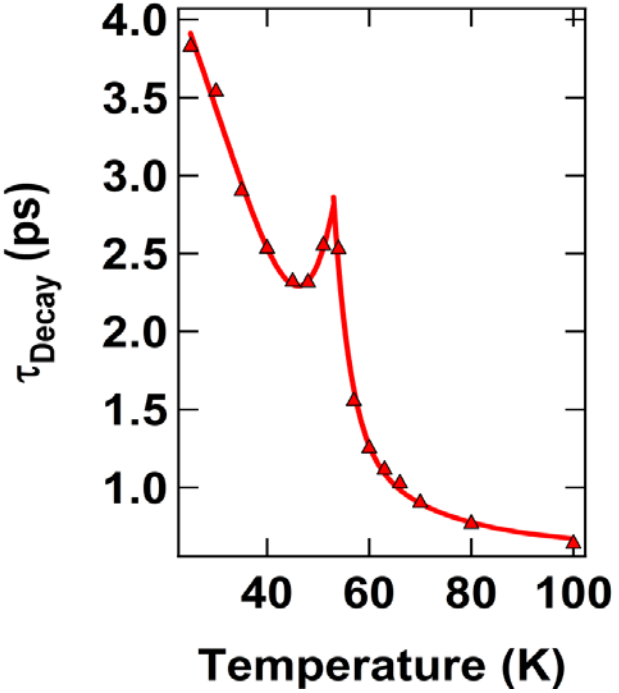
$\tau_{qp}(T_c) \approx 3ps$

Hg1223 (T_c = 120 K)



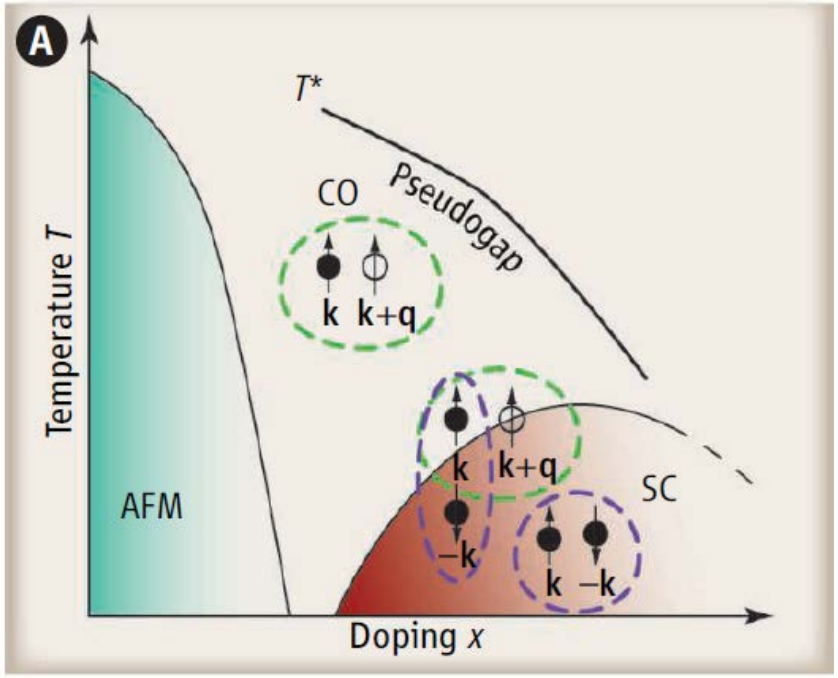
Demsar, Kabanov, Mihailovic (2000)

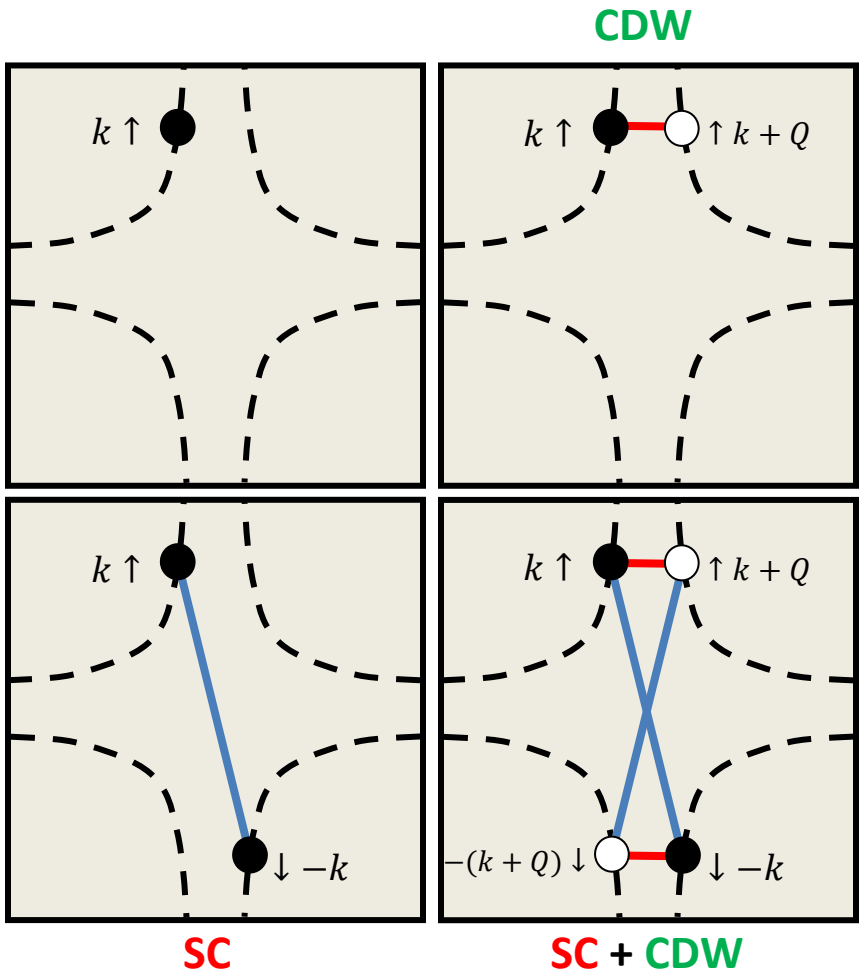
YBCO Ortho II (T_c = 61 K)



Quasiparticle lifetime is a probe of coherence factors

Lifting the Fog of Complexity
Dirk K. Morr
Science **343**, 382 (2014);

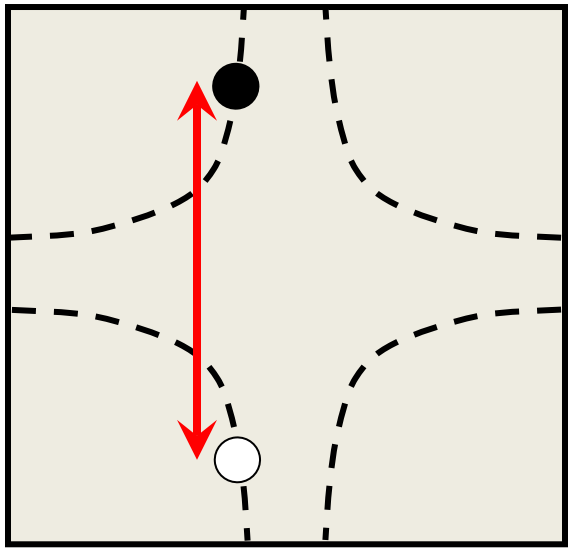




How coherence manifests in recombination

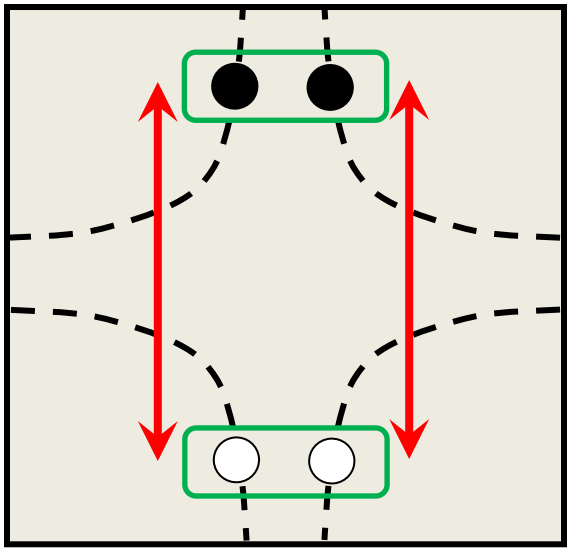
Recombination rate $\gamma(\varepsilon, \varepsilon') =$ Bare rate $\times$ coherence factor

Bare recombination rate γ_0



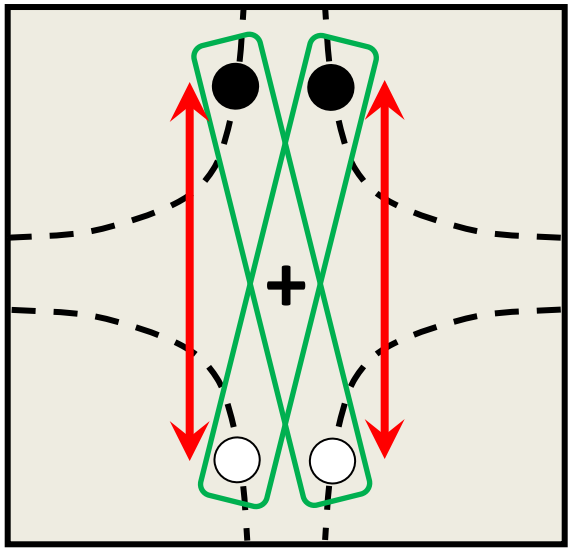
Incoherent normal state

CDW pairing: $\gamma \to 0$



CDW coherence

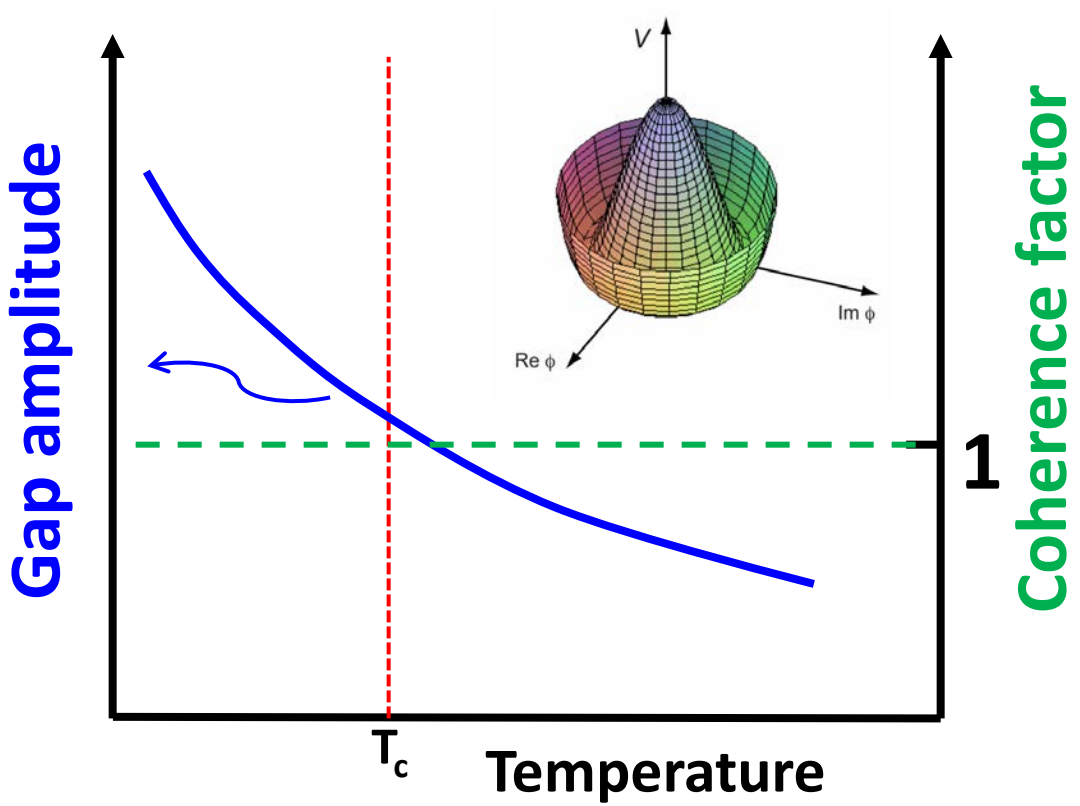
SC pairing: $\gamma \to \gamma_0$



SC coherence

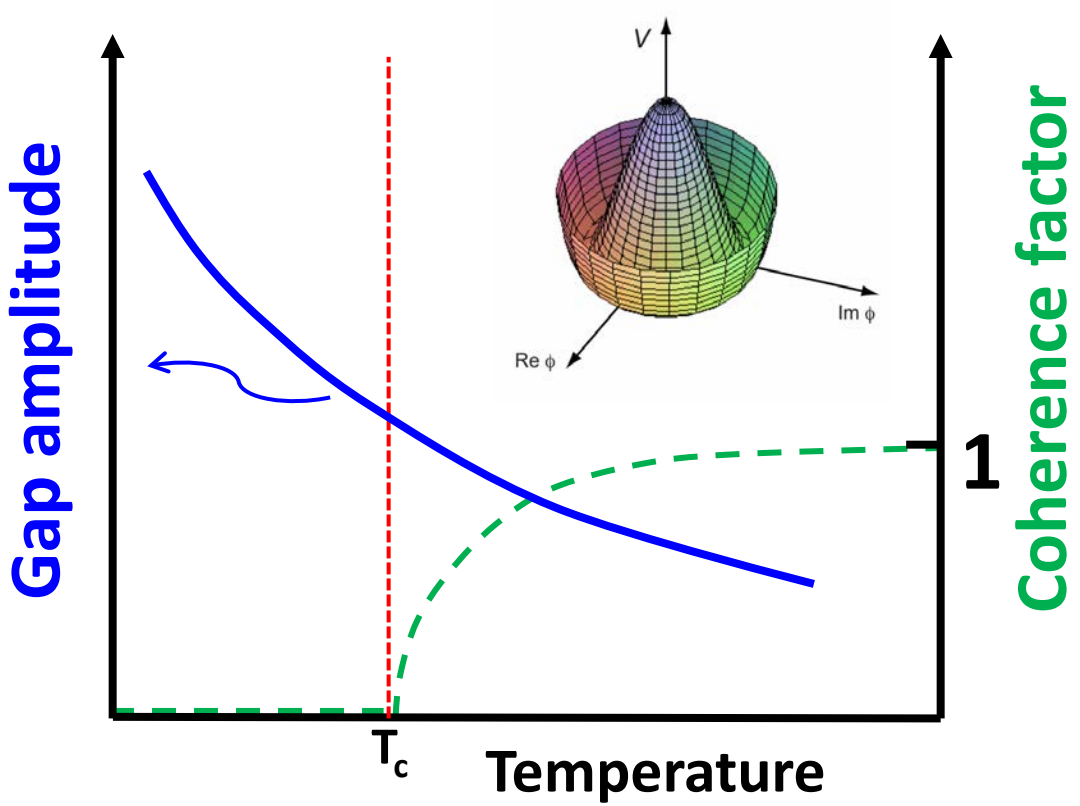
Phase fluctuation picture: superconductivity only

Superconducting U(1) phase fluctuations



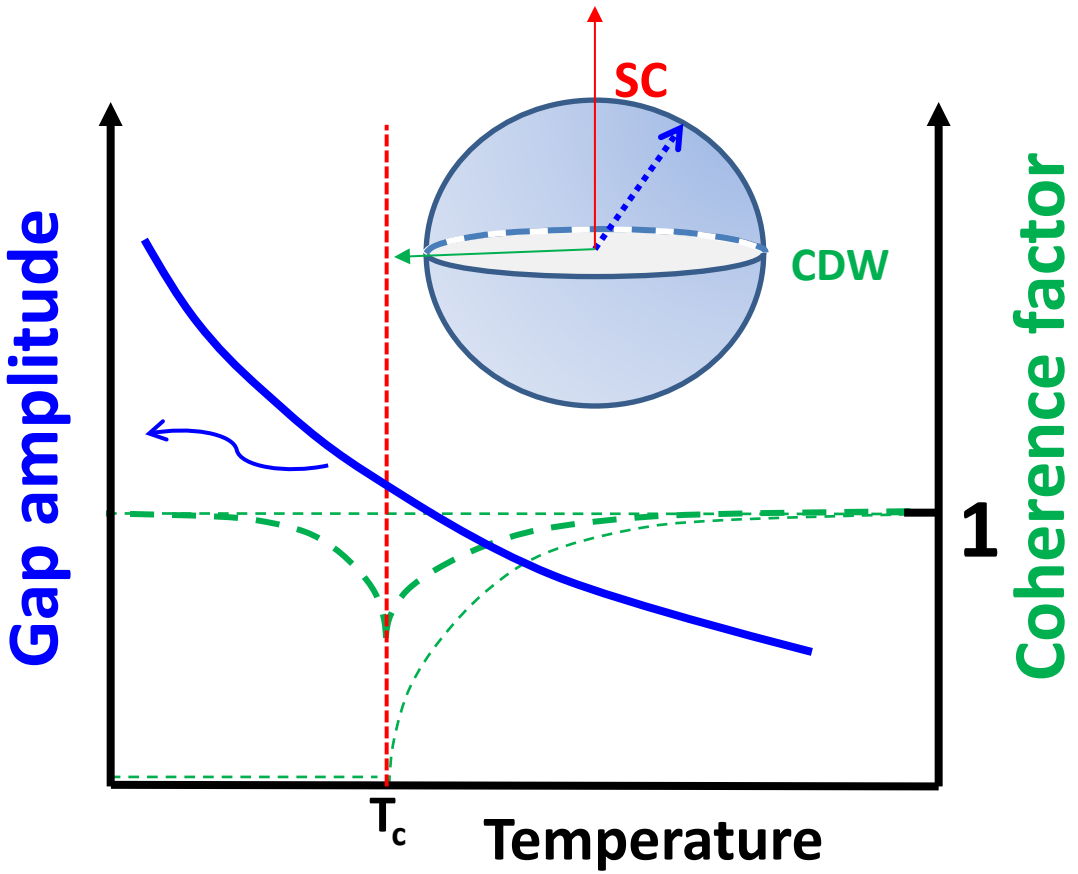
Phase fluctuation picture: CDW only

CDW U(1) phase fluctuations



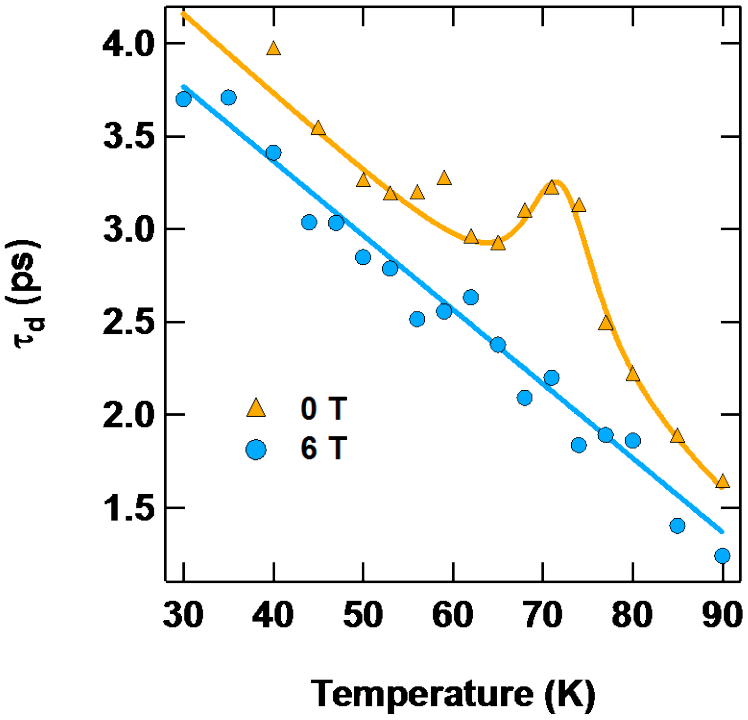
Combined SC and CDW U(1)⊗U(1) phase fluctuations

Hayward et al. (Sachdev group)

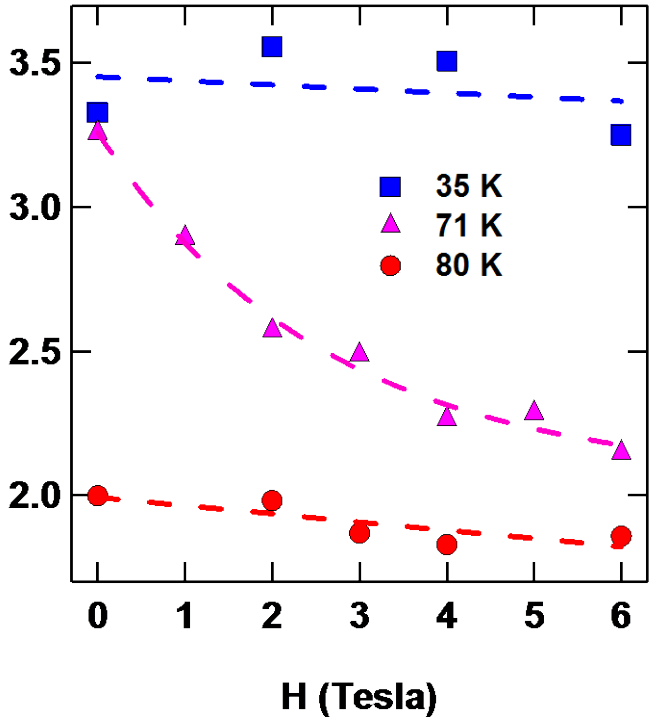


Recent result for B-field dependence of cusp

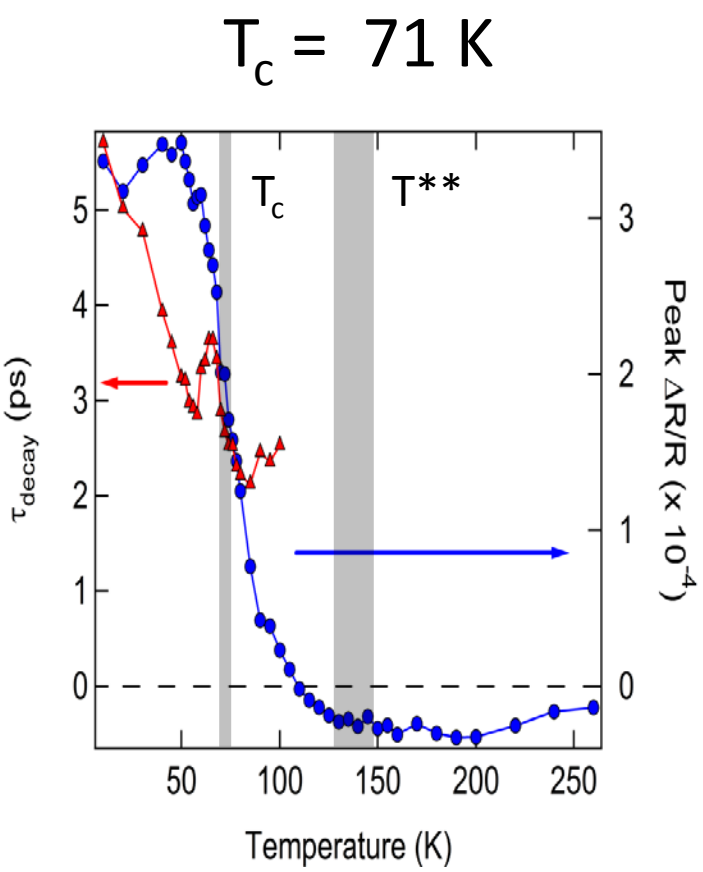
Lifetime vs. T for 0 and 6T



Lifetime vs. H



Conclusions from $\Delta R(t,T)$



- $\Delta R(t=0)$ detects gap opening near T_{CDW}
- No feature in $\Delta R(t=0)$ at T_c
- Quasiparticle lifetime has cusp at T_c
- Possible explanation in terms of Cooper pairing of CDW quasiparticles and associated coherence factors
- Momentum resolved probes of coherence factors would be very useful at this stage.

Acknowledgments

UC Berkeley

U. Minnesota

UBC

MPI Stuttgart

Jamie Hinton (graduate student)

Acknowledgments

UC Berkeley	**Jamie Hinton** (graduate student) Jake Koralek, Giacomo Coslovich Prof Ashvin Vishwanath (theory)
U. Minnesota	**Martin Greven** Guichan Yu, Mun Chan, Neven Barisic
UBC	**Ruixing Liang**, Doug Bonn, Walter Hardy
MPI Stuttgart	**Bernhard Keimer** Mathieu Le Tacon, Toshinao Loew